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## Monterey, California

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ACOUSTIC POSITIONING OF THE NPS
AUTONOMOUS UNDERWATER VEHICLE (AUV II)
DURING HOVER CONDITIONS

by

Kevin A. Torsiello      DTIC QUALITY INSPECTED 2

March 1994

Thesis Advisor:                         Anthony J. Healey

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The ability to take position, in a dynamic environment, relative to a local stationary object, is vital to many planned missions for the Naval Postgraduate School's Autonomous Underwater Vehicle (AUV II) project, such as bottom surveying and mine hunting. The AUV II can achieve this ability through the use of its sensors along with stern propulsion motors and tunnel thrusters.

The sensors employed by the AUV II include a free directional gyro and independent self-sonar which provide acoustic positioning data without the aid of a transponder net.

Described in this thesis are the details of the internal subsystems of the AUV II, and an examination of its positioning ability through the analysis of maneuvering experiments. Commanded motions of yaw, lateral and longitudinal positioning during hover conditions are studied.

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# ACOUSTIC POSITIONING OF THE NPS
# AUTONOMOUS UNDERWATER VEHICLE (AUV II)
# DURING HOVER CONDITIONS

by

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Submitted in partial fulfillment of the
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# ABSTRACT

The ability to take position, in a dynamic environment, relative to a local stationary object, is vital to many planned missions for the Naval Postgraduate School's Autonomous Underwater Vehicle (AUV II) project, such as bottom surveying and mine hunting. The AUV II can achieve this ability through the use of its sensors, along with stern propulsion motors and tunnel thrusters.

The sensors employed by the AUV II include a free directional gyro and independent self-sonar which provide acoustic positioning data without the aid of a transponder net.

Described in this thesis are the details of the internal subsystems of the AUV II, and an examination of its positioning ability through the analysis of maneuvering experiments. Commanded motions of yaw, lateral and longitudinal positioning during hover conditions are studied.

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# ACKNOWLEDGMENTS

especially the Engineering Duty Community, for providing me with this, among many career opportunities.

And most importantly, to my parents, for a lifetime of support and encouragement.

Thank you.  Thank you very much.

# I. INTRODUCTION

This chapter provides a discussion of the background information and outlines of the scope of study for this thesis.

## A. BACKGROUND

The applications of Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs) are subjects of increasing widespread interest by both civilian and military organizations.

The operation of ROVs is traditionally accomplished by the use of a physical tether, through which electrical power, control and sensory data are transferred between the vehicle and a surface ship. An ROV therefore, is under the continuous control of a human operator (pilot), and is dependent on and tethered to the host platform.

An AUV on the contrary, operates independently of any physical or electrical tether, and requires little to no intervention from an outside activity. This level of autonomous operation permits a greater scope of mission capabilities, and as such, is the subject of numerous research projects encompassed in the Autonomous Underwater Vehicle project at the Naval Postgraduate School, in Monterey, California, at the Monterey Bay Aquarium Research Institute, MIT Sea Grant, Charles Stark Drake Laboratories, Woods Hole Oceanographic Institute, Florida Atlantic University and the Naval Undersea Warfare Center, Newport, Rhode Island, amongst others.

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Future missions planned for the AUV project include environmental surveying, search and mine hunting missions. Vital to the accomplishment of these types of missions, is the capability for the vehicle to position itself in the vicinity of a stationary object or change its position with respect to an object, within a dynamic environment.

The ability to accurately maneuver itself, at relatively high speeds, within a confined environment, has been demonstrated by the second generation design of the NPS AUV (AUV II) (Warner, 1991). The ability to achieve accurate dynamic positioning, during hover conditions, based on the vehicle's own acoustic data input, has been made possible, only recently, through several configuration changes to the AUV II. These configuration changes include the addition of a high frequency profiling self-sonar, and horizontal and vertical tunnel thrusters.

The profiling sonar installed in the AUV II, provides acoustic environmental and positioning data without the use of external signals or transponder networks. The performance of the sonar has been tested and verified by previous experimentation (Ingold, 1991).

The design and performance testing of the tunnel thrusters have been verified and documented by Good (1989), Cody (1992) and Brown (1993).

## B. SCOPE OF THESIS

The objective of this thesis is to experimentally examine the capability of the NPS AUV II to achieve accurate acoustic positioning, during hover conditions. It is the contention of this work that both lateral and longitudinal

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position of the vehicle can be maintained using high frequency onboard sonar returns without the use of a transponder net. Furthermore, that without ocean current disturbances, the precision of the positioning is limited only by the precision of the sonar and the threshold of operation of the propulsors, and stable motion is achievable.

Chapter II provides documentation of the major design and configuration changes incorporated into the AUV, which provide the capability for the vehicle to accomplish the hover positioning experiments.

Chapter III includes a description of the test facility, laboratory and equipment set-up used for the experiments. The procedures for the positioning experiments are also discussed.

The results of the positioning experiments are provided in Chapter IV, along with the development of a theoretical model and its comparison to the experimental data.

A summary of conclusions and recommendations for further study is discussed in Chapter V.

# II.  AUV II CONFIGURATION

Since the time of its original design (Good, 1989) and successful waterborne demonstration (Warner, 1991), several design and configuration concepts have been the subject of research surrounding the AUV project at NPS, resulting in numerous published theses. The result thus far has produced the current configuration of the AUV II, pictured in Figure 2.1.

This chapter provides a description of the major equipment groups which comprise the current configuration of the AUV  Each section discusses the nominal operating characteristics and ratings as applicable, and refers to figures within the text, or diagrams and the wiring list which are included in the appendices. The following equipment groups are discussed:

1.   Sensors (Environment and Vehicle).
2.   GESPAC M68020/30 Computer System.
3.   Propulsion and Maneuvering Equipment.
4.   Electrical Power Equipment.

A simplified block diagram of these major equipment groups is provided in Appendix A. This diagram shows the basic system power paths and the computer data transfer paths between the components.

The wiring list for the AUV II is provided in Appendix B.

Figure 2.2 shows the placement of the major equipment components in the AUV. As discussed in Good (1989), the propulsion and maneuvering equipment (control fins, tunnel thrusters and stern propulsion motors) is

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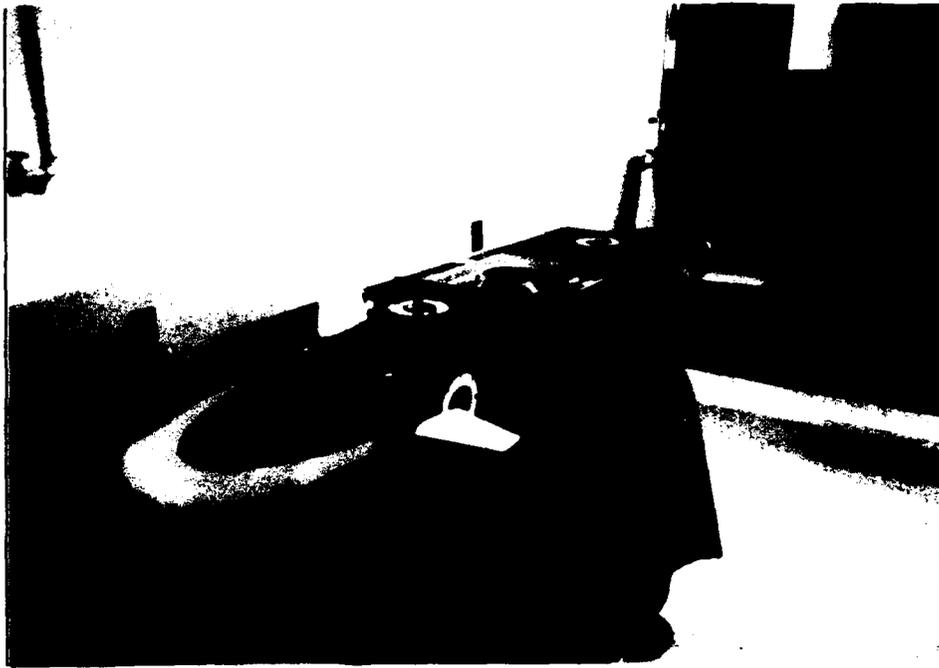
**Figure 2.1** AUV II

1 Nosepiece (Flooded)
2 ST-1000
3 Datasonics
4 ST-725
5 Flow Meter
6 Depth Cell
7 Control Fin Servo Motor
8 Horizontal Thruster
9 Servo Amp

10 Power/Run Plug
11 Serial Port Connector
12 Vertical Thruster
13 Rate Gyro
14 Vertical Gyro
15 12 VDC Battery
16 ACON Power Supply
17 Calex Power Supplies/
   CRYDOM Relays
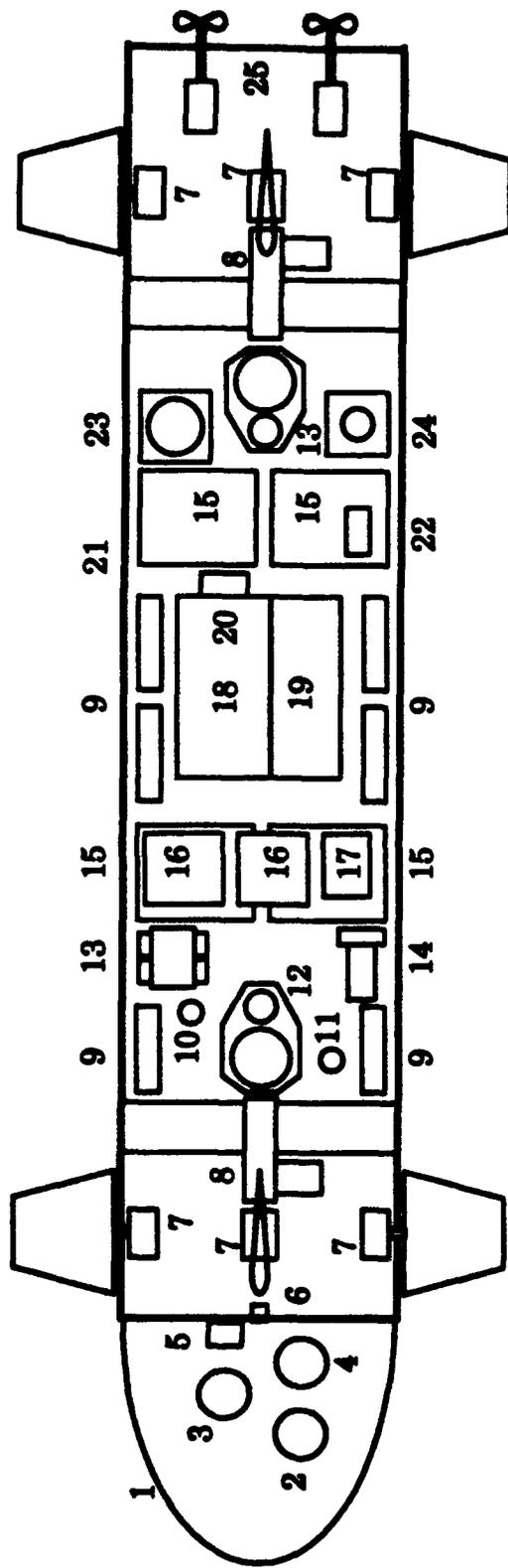
18 GESPAC (Execution Processor) OS-9
19 GESPAC (Tactical Processor) DOS
20 Synchro/Digital Converter
21 Pressure Hull (Air charged to 1 psi)
22 Inverter (Motor Inhibiter)
23 Free Directional Gyro
24 400 Hz Power Supply
25 Stern Propulsion Motors

**Figure 2.2** AUV II Configuration

arranged in the vehicle, to achieve the most efficient maneuvering capabilities. The remainder of the equipment is located to achieve the most favorable volume and weight distribution, and to minimize the length of the wire runs. The batteries therefore, are centrally located in order to keep the center of gravity close to the center of the vehicle body. The computer is located at the center of the vehicle body, with the served equipment located as close as possible to the computer.

Calculations of the centers of gravity and buoyancy are provided in Appendices C and D.

## A. SENSORS

The sensor systems incorporated into the AUV II provide the necessary input data, for both environment conditions and vehicle motion, to achieve autonomous vehicle operation and control.

### 1. Environment Sensors (Sonar Equipment)

The sonar suite consists of three types of sonar transducers with primary functions being horizontal environmental surveying (profiling), target imaging (scanning) and bottom surveying (depth measuring). The three types of sonar used for these functions, are respectively; the Tritech ST-1000 and ST-725 sonar and the Datasonics PSA-900 altimeter. Placement of the transducers, in the (flooded) nosepiece section of the AUV is shown in Figure 2.3.
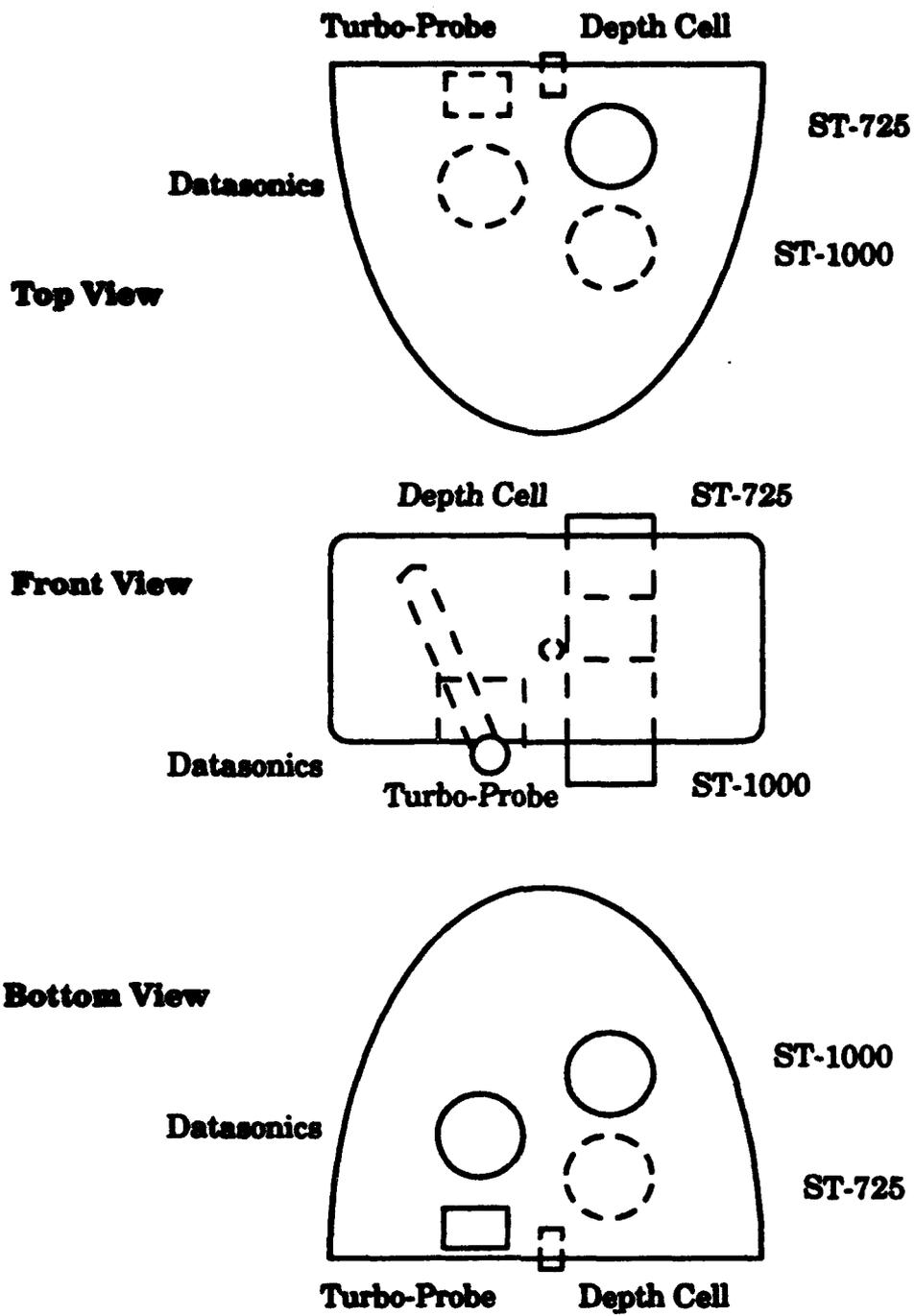
**Figure 2.3** Sensor Location (Nosepiece Section)

### a. *Profiling Sonar (Tritech ST-1000)*

The profiler is the model ST-1000 sonar, manufactured by Tritech International, Ltd. This unit is a compact system, operated by a PC compatible computer and is integrated with the ST-725 scanning sonar.

The ST-1000 sonar head operates at a frequency of 1250 kilohertz (1000 kilohertz, nominal), with a one degree conical beam. It requires 24 to 28 volts (DC) power at 800 miliamps, and can be operated at depths up to 4900 feet, over eight selectible ranges between three and 160 feet.

The ST-1000 can be operated in two modes; Sector Profiling or Sector Sonar Scanning. The Profiling mode provides 360 degree coverage, where the delay time to the first echo is sensed and returned to the device serial port connector. The Scanning mode is continuous, and can be used for horizontal sector scan, or for vertical left or right side direction coverage. In this mode, the intensity of the returning echoes are sensed as a function of delay time and returned to the device serial port connector as a string of values, one in each of 64 range pixels. At larger total ranges, full range is divided into 128 range pixels. For the shorter ranges, a sonar pixel will be 9.3 centimeters long by 1.8 degrees wide. Intensities are scaled from one to 15, where 15 represents the highest strength.

The ST-1000 sonar head is mounted vertically, in the AUV, protruding through the bottom of the nosepiece.

### b. Scanning Sonar (Tritech ST-725)

The scanning sonar is the ST-725, also manufactured by Tritech. It operates at a frequency of 725 kilohertz with a one degree by 24 degree fan beam.

The ST-725 sonar head is mounted aft of the ST-1000, but protruding through the top of the nosepiece.

### c. Depth Sonar (Datasonics PSA-900)

The depth sonar is the Model PSA-900 Sonar Altimeter, manufactured by Datasonics, Inc. It is microprocessor controlled.

The Datasonics operates at a frequency of 210 kilohertz, with a ten degree conical beam. It requires 15 to 28 volts (DC) at 100 miliamps and can be operated at depths up to 6500 feet, at ranges up to 90 feet.

The Datasonics transducer is installed as described in Good (1989), with a plastic cone, mounted in the nosepiece. Only one Datasonics transducer is used here, as opposed to the original configuration, and it is mounted facing downward, aimed through the bottom of the nosepiece.

### 2. Vehicle Sensors

The vehicle sensor components provide the input data for the position and motion of the AUV.

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### a. Gyroscopes

Three types of gyros were used to measure the vehicle's angular position and roll, pitch and yaw rates. All three types are manufactured by Humphrey, Inc.

*(1) Free Gyro.* The free gyro measures the yaw angle of the vehicle. The Model FG23-7102-1 is a two-degree-of-freedom unit which references its own case frame.

Its inner and outer gimbals have 360 degree and negative to positive 85 degree motion, which require 26 volts (AC), 400 Hertz input. The pickoff is an outer gimbal syncro control transmitter which outputs 11.8 volts (AC). The gimbals have a remote caging/uncaging device which requires 28 volts (DC) input.

The gyro motor requires 115 volts (AC), 400 Hertz, and spins at approximately 24,000 revolutions per minute. The Model PS27-0101-1 power supply provides the 400 Hertz (26 and 115 volts (AC)) input to the gyro.

The free gyro is located aft in the midbody section of the AUV. The wiring diagram for the free gyro is provided in Appendix C.

*(2) Vertical Gyro.* The vertical gyro measures the pitch and roll angles of the vehicle. The Model VG34-0301-2 is a two-degree-of-freedom unit with both axes slaved to local gravity.

It's inner and outer gimbals have 360 degree (roll) and negative to positive 80 degree (pitch) motion. The pickoff is a plastic

potentiometer, which outputs negative ten to positive ten volts (DC). Required input is 28 volts (DC).

The vertical gyro is located forward in the midbody section of the AUV. Since the vehicle body is rigid, gyro placement was a matter of arrangement rather than a matter of required location within the body.

(3) *Rate Gyros.* The rate gyros measure the roll, pitch and yaw rates of the vehicle. Each component of the Model RG02-2324-1 has single-degree-of-freedom motion along its designated axis, and is torsion spring mounted to produce gimbal displacements proportional to angular rate inputs.

Required input is 28 volts (DC). The pickoffs are resistance potentiometers which produce output voltages of negative ten to positive ten volts (DC). Maximum rates are 360, 90 and 90 degrees per second for roll, pitch and yaw.

The rate gyros are located forward in the midbody section of the AUV.

b. *Depth Cell (PSI-Tronix)*

Vehicle depth is measured using a differential pressure transducer manufactured by PSI-Tronix, Inc.

The PWC series (S11-131) is a strain gage based transducer which operates from zero to 15 pounds per square inch (depth to approximately 34 feet), referenced to one atmosphere. It requires 12 to 18 volts (DC) supply and outputs zero to ten volts (DC).

The probe for the depth cell is located in the nosepiece section of the vehicle in the aft bulkhead, in order to permit contact with the water at the vehicle's depth, with minimal flow.

### c. *Vehicle Speed Sensor (Turbo-Probe)*

The vehicle speed through the water is measured by a Turbo-Probe turbine flow meter, manufactured by Flow Technology, Inc.

The transducer is an axial rotor element, mounted at the end of a strut. The strut houses an electromagnetic pickoff assembly which generates electrical pulses of a frequency proportional to the rotor speed and flow velocity. The flow meter has an operating range of one tenth to six feet per second.

The flow meter is used in conjunction with the LFA-307 Range Extending Amplifier, also manufactured by Flow Technology. This amplifier is used for signal conditioning to insure good linearity at low flow velocities.

The flow meter is mounted in the nosepiece section of the AUV with the rotor element protruding through the bottom of the nosepiece.

### d. *Motor RPM Indicator (Hewlett-Packard)*

Hewlett-Packard Model HEDS-5000 series optical encoders are used to measure motor speed.

These encoders are configured with a lensed LED source, an integrated circuit (IC) with detectors and output circuitry, and a code wheel which rotates between the emitter and detector IC. Rotation of the code wheel generates a pulsed input which the IC circuitry processes to produce a digital

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pulsed output. Rotation speed is measured in terms of the pulse count per unit time, or the time width of successive pulses. The encoders require a supply voltage of one half to seven volts (DC) input and operate up to 30,000 revolutions per minute.

Each thruster and stern propulsion motor is configured with an encoder attached to its shaft.

## B. GESPAC M68020/30 COMPUTER SYSTEM

The function of providing real time control of the AUV II is accomplished through the use the GESPAC M68020/30 series computer system and various input/output control cards.

The OS-9 Operating System is used in the GESPAC. It provides real time, multi-tasking capability. C language is the source code. It is independent from the input/output devices.

The software package PC Bridge (trademark of GESPAC, Inc.), is used to communicate between the GESPAC and an external IBM PC for the purposes of file transfer. As the processor system is an embedded real time processor, it operates on a single board without the benefit of an associated hard disc for storage of memory modules. Only operating system modules are "burned" into EPROM, thus run modules that form the vehicle control functions at run time must be loaded from an external computer into the embedded processor.

The major components of the embedded computer system are positioned in a twelve card cage, located in the midbody section of the vehicle. Communication with the GESPAC is accomplished through an RS-232 serial

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communications port, located on the top of the vehicle, through a watertight connector and a sufficiently long, lightweight watertight cable.

The following sections give a brief description of the major components of this system. The paths for data input/output between the components are shown in the block diagram of Appendix A.

### 1. GESMPU-20 Micro Processor Unit

The GESMPU-20 module uses a 32 bit 68020 microprocessor built into a single board. The microprocessor uses a non-multiplexed G96 bus with 32 bits of address and 32 bits of data. The board runs at 25 megahertz and has an associated two megabytes of CMOS Dynamic RAM, on an adjacent card. Its power requirement is positive five volts (DC).

The GESMPU-20, through its device drivers and execution level real time control software, compiled into executable modules, controls all computer functions in the AUV.

### 2. GESMFI-1 Multi-Function Interface

The GESMFI-1 is a universal interface module with two RS-232 serial ports, two, eight-bit parallel ports and three 16-bit timers. The module runs with either one megahertz or two megahertz synchronous timing and has 50 bytes of CMOS RAM. The power requirements are positive five and negative to positive 12 volts (DC).

The GESMFI-1 interfaces with the 14-bit Synchro to Digital converter, which operates on the data from the free gyro. The MFI card

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provides the embedded processor with a digital data value of zero to 16384 ($2^{14}$), corresponding to one revolution (360 degrees) of the yaw angle gyro.

### 3. GESSIO-1B Serial Input/Output

The GESSIO-1B dual interface module provides two RS-232 capable asynchronous serial ports. The power requirements are positive five and negative to positive 12 volts (DC).

The GESSIO-1B provides the interface for the ST-725 and ST-1000 sonar transducers.

### 4. GESPIA-3A Peripheral Interface Adapter

The GESPIA-3A has two parallel 16-bit input/output ports and four 16-bit timers. The power requirement is positive five volts (DC).

This module provides the interface for the free gyro cage/uncage command and status signals. It also provides an input for the Datasonics sonar transducer, the CRYDOM relays and the Calex power supplies. It controls the Transistor-Transistor Logic (TTL) which provides the switching signals for the relay/power supply system.

### 5. GESADA-1 AND GESADA-2 Analog/Digital Interfaces

The GESADA-1 and GESADA-2 modules provide analog to digital (A/D) and digital to analog (D/A) functions. The GESADA-1 module has a 16 channel, ten-bit A/D input section and a four channel, ten-bit D/A output section. The GESADA-2 module has a 16 channel, ten-bit A/D input section. Both modules require positive five and negative to positive 12 volts (DC).

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The GESADA-1 module interfaces the outputs from the Diagnostics module. The GESADA-2 module interfaces the inputs from the vertical and rate gyros, the depth cell and the Datasonics transducer.

**6. GESDAC-2B Digital/Analog Converter**

The GESDAC-2B module provides an 8 channel, 12-bit D/A output. Its power requirement is positive five volts (DC).

This module interfaces the inputs to the propulsion and thruster motor servo amps.

**7. GESTIM-1A Multiple Timer Modules**

The GESTIM-1A modules provide the System Timing Control (STC) functions. Each module has five, 16-bit channels and a real time clock/calendar function. The power requirement is positive five volts (DC).

Five GESTIM-1A timing modules are used in the AUV which coordinate the signals between the tachometer sources (thruster and stern propulsion motor speed indicators, flow meter and control surface servo motors).

**C. PROPULSION/MANEUVERING EQUIPMENT**

The propulsion and maneuvering systems are comprised of three groups of equipment; control surfaces, stern propulsion and thrusters.

### 1. Control Surfaces

The development of the design of the control surfaces is presented in Good (1989). The shape used for the AUV II application is the NACA 0015 foil section.

Two cruciform arrangements of control surfaces are used; one arrangement forward and one aft, on the midbody section of the AUV. This arrangement provides highly efficient maneuvering capability in both the horizontal and vertical planes as evidenced by previous waterborne testing of the AUV (Healey and Marco, 1992).

The control surfaces are positioned through the use of radio controlled aircraft servo motors. Airtronics Model 94510 servos are installed, one for each control surface. These motors have a maximum torque rating of 110 ounces-inches (6.875 pound-inches) , and a response time of one half second for a zero to 90 degree movement.

### 2. Stern Propulsion

The AUV II is configured with a conventional twin screw propulsion system. Detailed development of the design is provided in Good (1989).

A commercially purchased running gear hardware kit, manufactured by Gato/Balao, Inc., is installed. The kit consists of two brass propellers, stainless steel shafts and three inch brass stuffing tubes. Two, four blade, four inch diameter propellers are installed, each capable of providing approximately five pounds of thrust at full load (Saunders, 1990, Coty, 1992).

Electric DC servo motors are used for the stern propulsion units. The PITMO DC Model 14202 series motor, manufactured by Pittman, Inc., has a stall torque of 106 ounce-inches, a no load speed of 3820 revolutions per minute and a peak power draw of 333 Watts. Operating at 24 volts (DC), the motor has a no load current rating of 0.230 amps.

### 3. Thrusters

The AUV II is configured with four tunnel thrusters which provide the capability for slow speed maneuvering, hovering and station keeping. The thrusters are mounted in pairs, one mounted horizontally, one vertically; each pair is mounted forward and aft, in the midbody section of the AUV.

Each thruster assembly consisted of a DC servo motor, a reduction gear and housing assembly, a propeller assembly and thruster tunnels.

The servo motors used for the thrusters are the same as those used for the stern propulsion units described above; PITMO DC Model 14202 series.

The reduction gear is a single stage, single reduction spur gear configuration. The pinion and gear are made of Delrin (trademark of Winfred M. Berg Company). Both the pinion and gear have a pitch of 24 teeth per inch. The pinion has 45 teeth and a pitch diameter of 1.875 inches, and the gear has 90 teeth and a pitch diameter of 3.750 inches. The resulting reduction ratio provided is two to one. The gear is configured as a ring gear and is fitted around the propeller and hub assembly. The reduction gears are assembled into an aluminum housing to which the thruster servo motors are mounted. (Cody, 1992)

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The propeller and hub assembly is made of brass. The propeller is three inches in diameter, and has four blades mounted at 45 degrees. The blade angle is constant along its length, and the blade has zero camber which permits equal thrust in both forward and reverse directions of rotation. The propeller and hub assembly is mounted on a stainless steel shaft and the thrust/journal bearings are made of Teflon. (Cody, 1992)

Aluminum struts, mounted in the thruster tunnels, support the propeller shaft, oriented axially in the thruster housing. The tunnels have an inside diameter of three inches, and are mounted in two sections on either side of the thruster housings, placing the thruster housings at the midpoints of the tunnels. The horizontal tunnels are 16.5 inches and the vertical tunnels are ten inches in length, corresponding to the width and height of the AUV.

The modeling and performance analysis of the thruster assemblies have been the subject of several theses, including Good (1989), Cody (1992) nd Brown (1993).

## D. ELECTRICAL POWER EQUIPMENT

The objective of the original design considerations for the power requirements of the AUV II was to provide adequate energy onboard which would support all vehicle functions for at least an hour of completely autonomous operation. The installed electrical system provides enough power to run the vehicle's onboard computer, sonar and electronics systems in addition to power for mobility.

This section describes the major components of the electrical power system.

### 1. 24 Volt Battery Packs (Panasonic)

Two 24 volt (DC) battery packs provide the main power source for the AUV. Each battery pack is made up of two, 12 volt (DC) Panasonic Model LCL12V38P rechargeable, sealed lead-acid batteries connected in series. The batteries weigh 31.5 pounds, and have nominal capacities of 34.0 amp-hours (ten hour rate) and 38.0 amp-hours (20 hour rate).

The series battery packs provide 24 volts (DC) power to the following equipment:

1. Rate gyros.
2. Vertical gyro.
3. 400 Hertz power supply for the free gyro.
4. ACON computer power supplies.
5. CRYDOM relays.
6. Calex power supplies.
7. Six, PMW servo amplifiers (thruster and stern propulsion motors).
8. Tachometer sources (thruster and stern propulsion motor speed indicators, Turbo-probe).

The battery packs are located in the midbody section of the AUV, one forward and one aft of the GESPAC computer cage.

### 2. ACON Power Supplies

Two ACON Model R100T2405-12TS inverter/power supplies are installed to provide power to the computer systems. The two power supplies

are independent and provide positive five and negative to positive 12 volts (DC).

The power supplies are mounted in the midbody section above the forward battery pack.

### 3. Calex Power Supplies

The Calex Models 12S15, 48S15 and 12S5 power supplies provide positive five and negative to positive 15 volts (DC) for the following equipment:

1. Reference source for the rate gyros and vertical gyro (+/-15 volts (DC)).
2. Datasonics sonar (+15 volts (DC)).
3. Depth cell (+15 volts (DC)).
4. GESTIM-1A timer cards (+15 volts (DC)).
5. Control surface servo motors (+5 volts (DC)).
6. CRYDOM relays (+5 volts (DC)).

The power supplies are mounted in the midbody section above the forward battery pack.

### 4. CRYDOM Relays

The CRYDOM Model 6300 relays provide the voltage switching using TTL logic input from the GESPIA-3A modules. Power is supplied to the following components:

1. Tritech sonar (ST-1000 and ST-725) (+24 volts (DC)).
2. Cage/uncage voltage for the free gyro (ground path).

### 5. Servo Amplifiers (Advanced Motion Controls)

Motor speed for the thruster and stern propulsion motors is controlled through the use of Advanced Motion Controls PWM Model 30AD8DD servo amplifiers. One amplifier is used for each motor. The PWM servo amplifier uses a zero to ten volt control signal to modulate the pulse width of a 24 volt, five to 45 kilohertz (load dependent) output signal to the motor. Direction of the motor is controlled by changing the polarity of the control signal.

The servo amplifiers are located in the midbody section of the AUV, mounted on the port and starboard bulkheads.

### 6. Synchro to Digital (S/D) Converter

The Synchro to Digital Converter is a 14-bit device designed at the Naval Postgraduate School. It uses an Analog Devices card which converts the phase components of the free gyro output signal to digital data.

The S/D converter is located in the midbody section and is mounted on the aft end of the GESPAC computer card cage. The wiring diagram for the S/D converter/free gyro is provided in Appendix C.

### 7. Inverter (Motor Inhibitor)

A signal inverter is installed between the GESPIA-3A module and the servo amps to prevent energizing the thruster or stern propulsion motors during computer system start-ups.

The inverter is located in the midbody section and is mounted above the aft battery pack.

# III. EXPERIMENTAL APPARATUS AND PROCEDURE

This chapter provides a description of the equipment and procedures used to conduct the hover positioning experiments for the AUV II.

Background information is discussed concerning the preparation of the AUV II vehicle, the lab and support facilities and the test equipment, followed by an outline of the procedures used for the experiments and data collection.

## A. EQUIPMENT PREPARATION

The equipment used for the hover positioning experiments are categorized into three groups; the AUV II vehicle, the test facility and the programmed software code.

### 1. AUV II Vehicle

Over the course of the thirty months since the vehicle completed its last waterborne tests, numerous configuration changes have been incorporated into the AUV, the results of which were presented in Chapter II. Many man-hours were consumed, involving the expertise of the Mechanical Engineering Department machine shop personnel, electronics technicians, staff, ... and a few students.

New equipment groups installed in the AUV include sonar, gyros, power supplies, speed sensors and computer systems, however, the equipment which provide the means to accomplish the objective of this thesis are the thrusters. The location of the horizontal thrusters, forward and aft of the

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vehicle's center of gravity permit rotation and lateral translation, while the vehicle is hovering.

The final design concept for the thrusters was completed and a prototype assembly was manufactured and satisfactorily tested (Cody, 1992). The three remaining thruster assemblies were then constructed and the four units installed in the AUV.

## 2. Lab and Test Facility

The test facility for the AUV project is located in building 230 of the Naval Postgraduate School Annex. The facility houses a 18,000 gallon capacity test tank which measures 20 by 20 by 6 feet. Other equipment include a filtration and recirculation system, hoist, catwalk and external computers.

The external computers include an IBM PC clone 486 with a VGA graphics monitor, a clone 286 PC and the GESPAC Development System, which is a replication of the in-vehicle system with a hard drive, C code cross-compiler and PC Bridge software for transferring compiled modules of code to and from the vehicle.

In preparation for the hovering experiments the interior of the tank was painted with white epoxy, and a 2.5 foot square grid pattern was laid out along the bottom and sides of the tank. This permitted good visibility of the vehicle, and provided a reference for vehicle pre-positioning and motion observation, during testing. A catwalk was installed across the top of the tank for vehicle launch and recovery, and experiment observation.

### 3. Computer Software

In order to support the basic operating functions of the AUV in addition to executing the positioning experiments, numerous software programs were written and installed in the onboard GESPAC and external control computer systems. The development of the software programs is the subject of a doctoral dissertation, currently in progress by David B. Marco.

Some of the AUV operations supported by the software include the following:

1. AUV system start-up.
2. Free gyro caging/uncaging.
3. Gyro zeroing functions.
4. Sonar operations.
5. Sensor data input functions (A/D).
6. Command positions for motion experiments.
7. Control law functions for each operating mode of behavior.
8. Command data output functions (D/A).
9. Data storage for analyses.

It should be noted that independent software modules for debugging subsystem operations are not only desirable, but essential to the calibration and verification of vehicle functions.

## B. EXPERIMENTAL APPARATUS

The equipment arrangement for the hovering motion experiments is shown in Figure 3.1.

**Test Tank (20' x 20' x 6')**
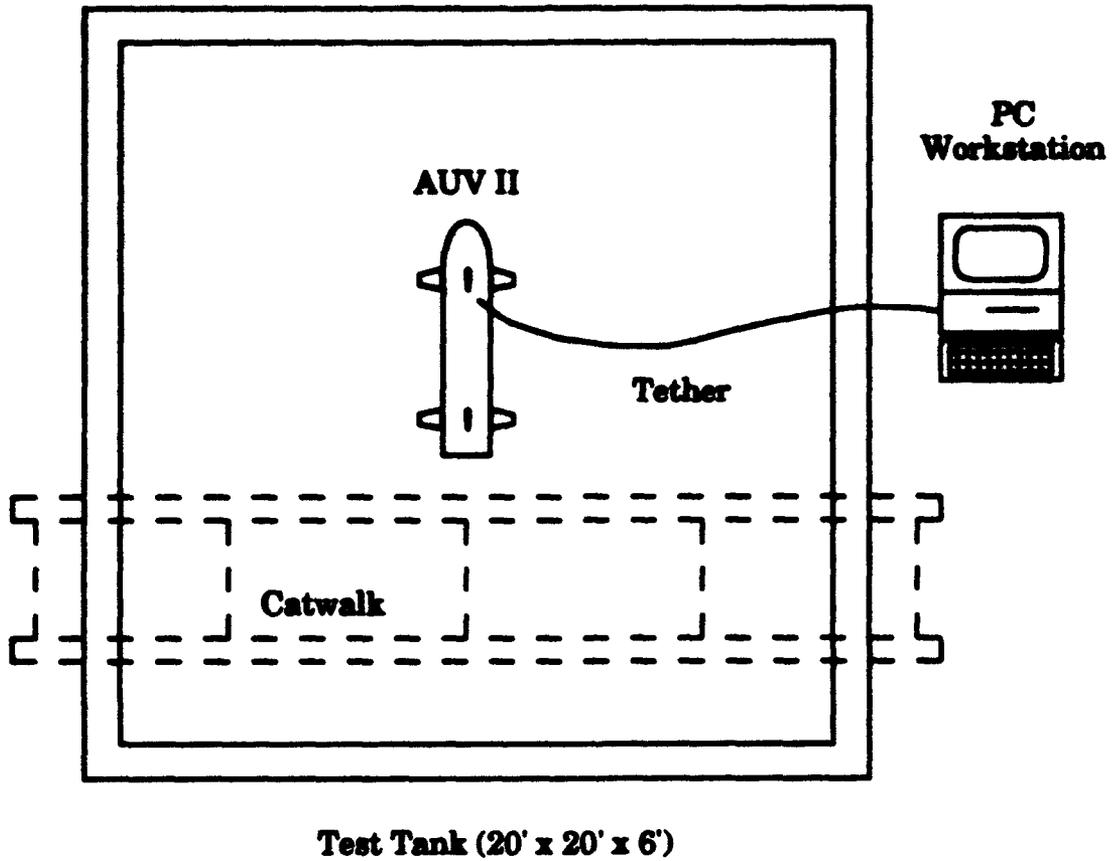
**Figure 3.1   Experimental Set-up**

For the purposes of conducting these experiments, an electronic tether was attached to the onboard GESPAC computer via the RS-232 connection. This provided a direct path for file and data exchange between the GESPAC computer and the external PC workstation running PC Bridge software.

The vehicle is lifted into the test tank via the hoist, and positioned for the start of each experiment by observers on the catwalk. The observers remain stationed on the catwalk throughout the tests to recover the vehicle or prevent damage should an equipment casualty occur.

The vehicle is operated externally through the PC workstation, however the serial link is used only for file and data transfer. Motion commands are built into the run program through screen entry, but once entered, the vehicle is completely independent of any further commands for the operation. Data files recorded for each experiment are down-loaded to the PC workstation.

The AUV II vehicle, test tank and PC workstation are pictured in Figures 3.2 and 3.3.
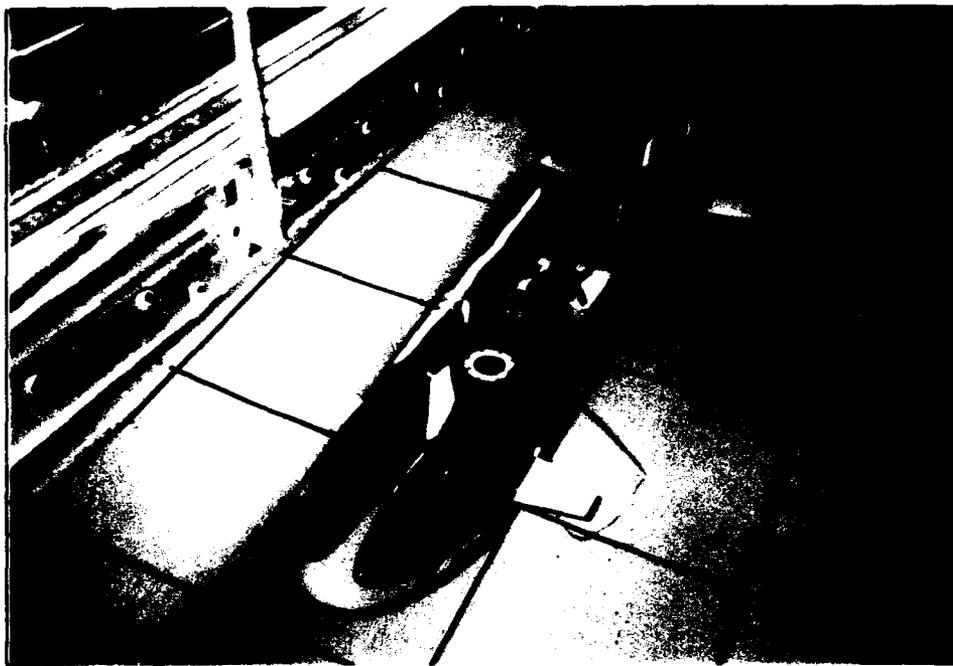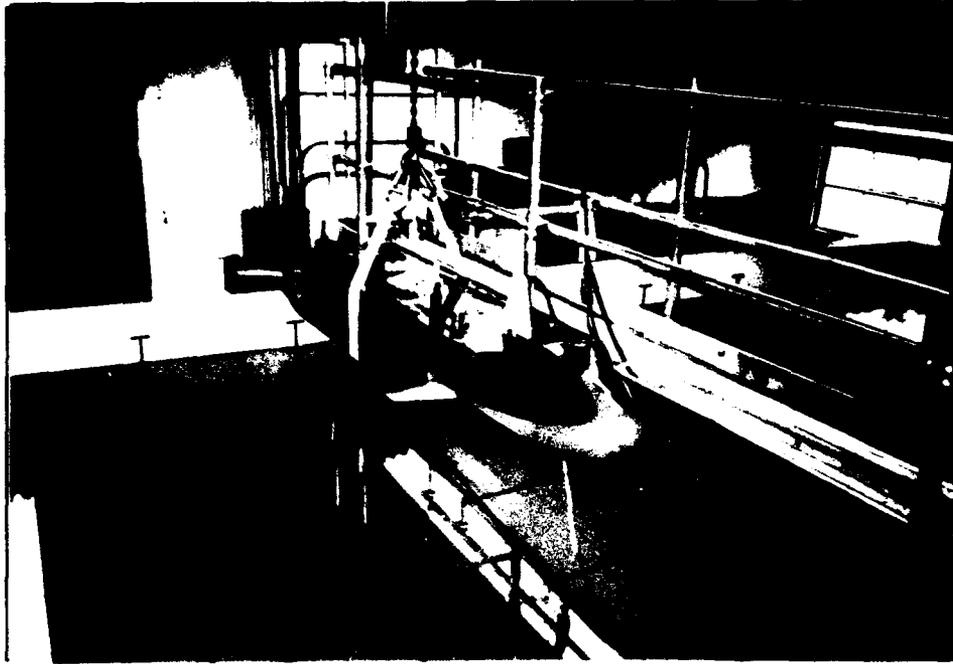
**Figure 3.2** AUV II and Test Tank

**Figure 3.3**   AUV II and PC Workstation

## C. EXPERIMENTAL PROCEDURE

This section describes the procedures used to calibrate the test equipment and outlines the three types of hover positioning experiments, including data collection.

### 1. Rate Gyro Calibration

Calibration of the rate gyro was required due to a new power supply being used for its input. The new power supply also produced a change in the range of output voltages from the gyro.

It was anticipated that both a scale factor and a bias error would be electronically introduced into the gyro output.

An additional bias error was expected as a result of the zeroing procedure to be used at the start of the experiments. During this procedure, the vehicle is held as motionless as possible in the tank. As the experiment starts, before any control motion begins, a segment of the run code reads the sensors, taking initial position readings of the vehicle relative to the environment. Average values of positions and rates are calculated and used as zero points for the following test rate and position measurements. Unless the vehicle is perfectly motionless (which is impossible in this test facility), there will be some rate bias introduced, however it was expected that this would be small.

Referencing the right-hand global and body fixed coordinate systems, as shown in Figure 3.4, the scale factor (SF) and bias factor (BF) errors are modeled by the following equation:
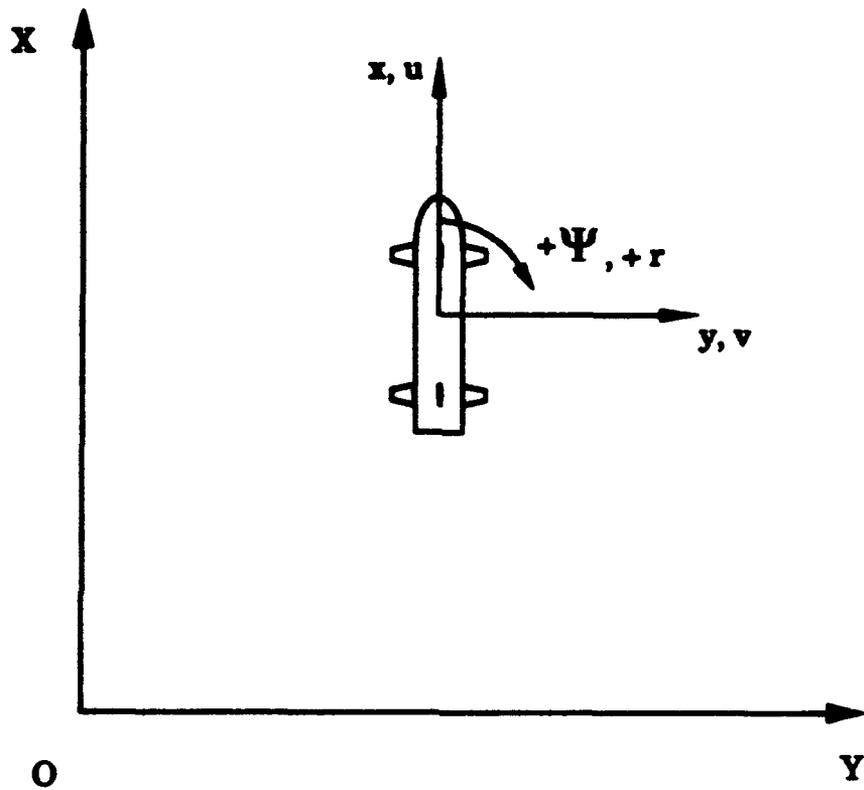
**Figure 3.4    Right-Hand Global and Body Fixed
Coordinate Systems**

$$r_{exper} = \left(D\left[\Psi_{exper}\right] - BF\right) \div SF$$

where it was considered that the precision of the heading gyro (drift rate less than six degrees per hour) was such that

$$D\left[\Psi_{exper}\right] \approx r_{true}$$

The experimental yaw rate can then be corrected by the following equation:

$$r_{true} = r_{exper} \times SF + BF$$

The true yaw rate could then be found by correlating the experimental yaw rate data to the derivative of the yaw position data using a first order least squares fit.

Since the vehicle, when placed in the tank, essentially behaved as an ideal rate table, it was decided to use the vehicle's own motion under a yaw position command to calibrate the rate gyro. This motion is shown in Figure 3.5. Inputs from the free gyro were used to determine the vehicle's yaw position.

The control laws for the yaw position commands were derived on the basis that the commanded moment is directly proportional to the differential thrust between the forward and aft lateral thrusters, where the thrusters are used in opposite directions. Additionally, the thruster force is proportional to the square of the applied motor voltage (using the absolute value to account for direction).

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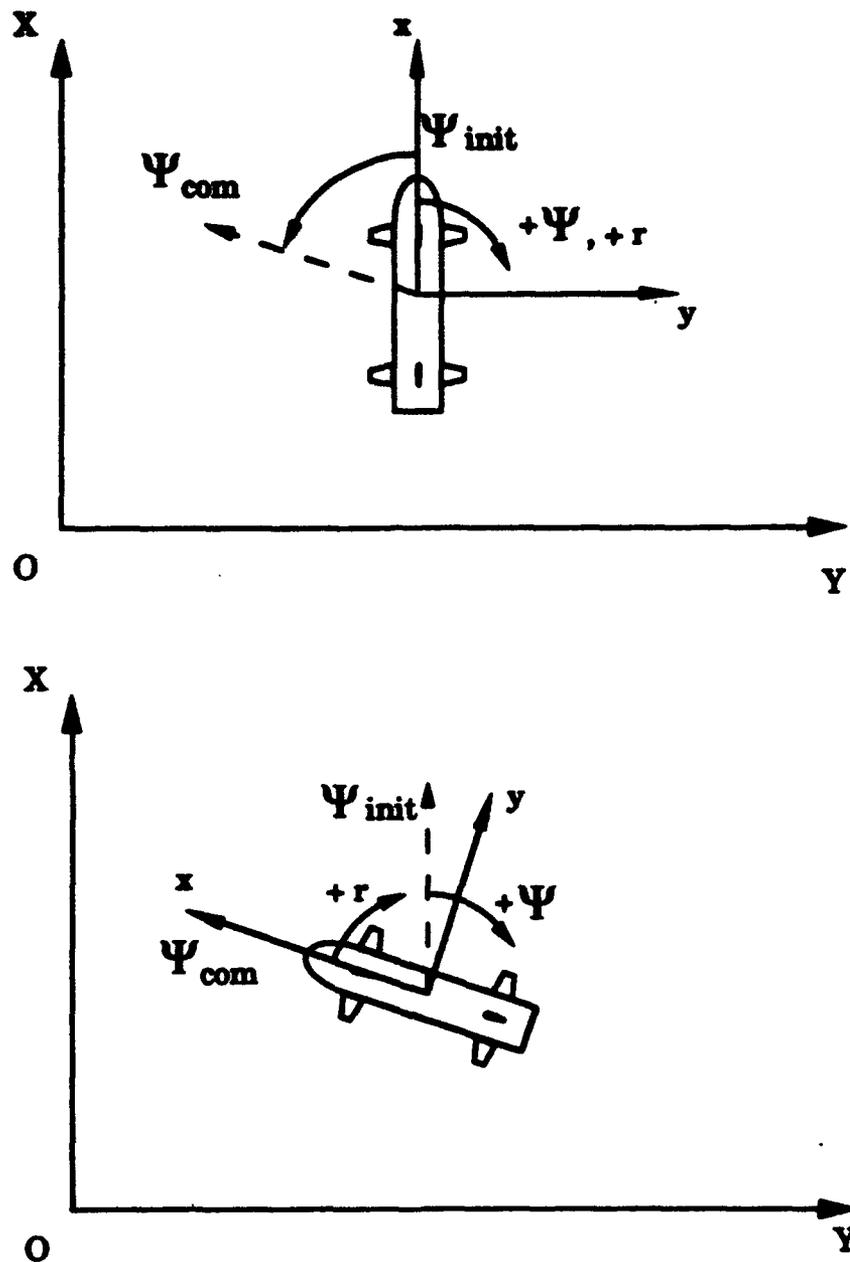
**Figure 3.5** Yaw Rate Calibration/Yaw Positioning Experiment

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$$M_{com} \propto \left( F_{Fwd\,Thrust} - F_{Aft\,Thrust} \right)$$

$$F_{Fwd\,Thrust\,(Yaw)} = -F_{Aft\,Thrust\,(Yaw)}$$

$$F_{Thrust} \propto V_{Thrust} |V_{Thrust}|$$

However, in order to keep the control effort linear, the position commands were generated using proportional derivative control laws for the thruster voltages. Based on the equations above, the control laws for the forward and aft thruster voltages are as follows:

$$V_{Fwd\,Thrust} = -K_\Psi \left( \Psi - \Psi_{com} \right) - K_r \left( r - r_{com} \right)$$

$$V_{Aft\,Thrust} = K_\Psi \left( \Psi - \Psi_{com} \right) + K_r \left( r - r_{com} \right)$$

$$K_r = K_\Psi \times T_{d\Psi}$$

The control law gains were selected heuristically, estimating that a full voltage control effort (24 volts) would be used for a yaw position error of $\pi/8$ (22.5 degrees), with a nominal time constant of one second. These estimates resulted in the following control law gains for yaw positioning:

$$K_\Psi = 60$$

$$T_{d\Psi} = 1$$

The position commands were given for yaw angles of (negative) 30, 60, 90, 180 and 360 degrees (relative to a starting position). Three trials were completed for each commanded position angle.

The data recorded included yaw position, yaw rate and forward and aft thruster voltage inputs as functions of time. Figure 3.6 presents the yaw position versus time and the yaw rate versus time curves for the three, 180

35
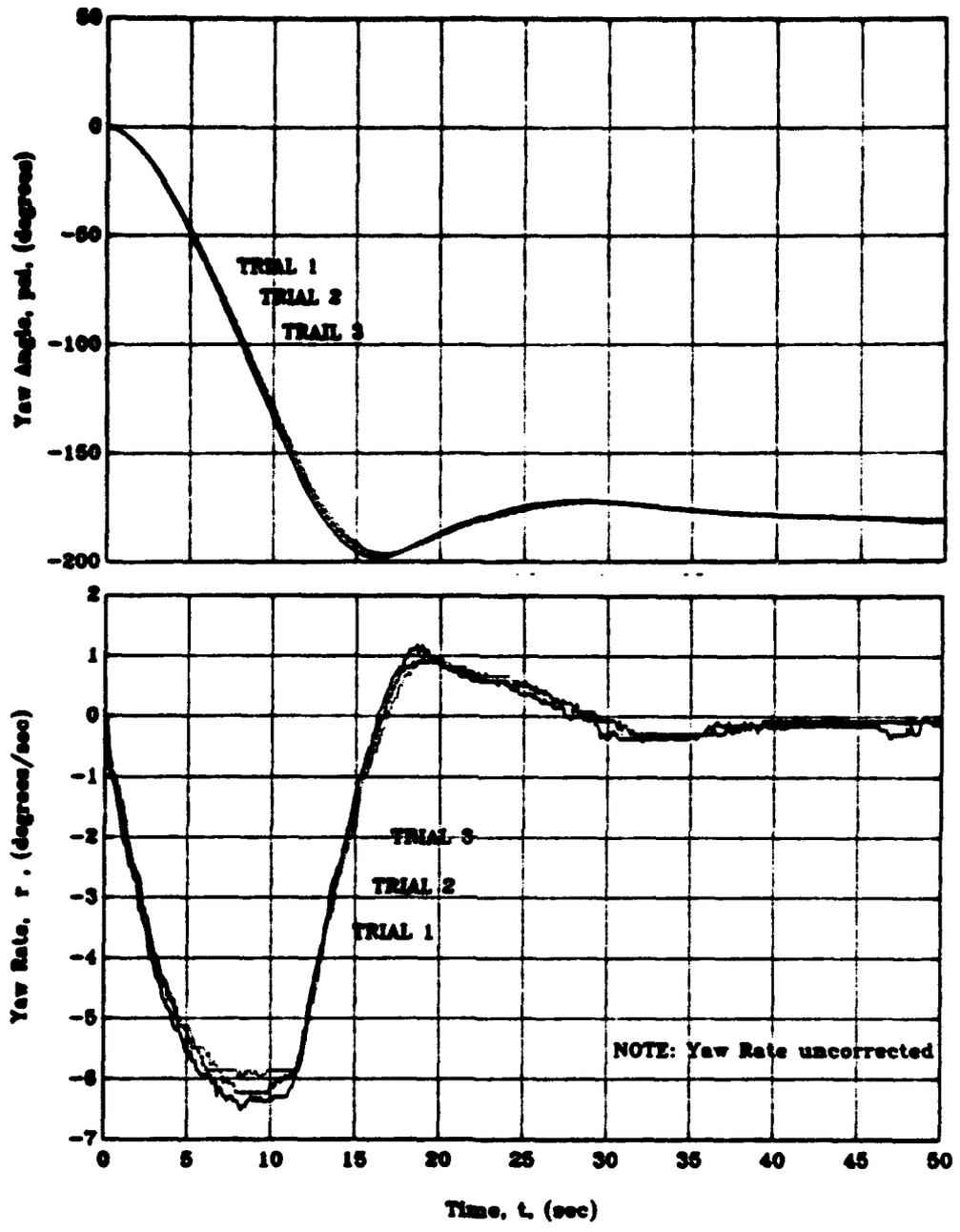
**Figure 3.6   Yaw Rate Calibration: 180 Degree Test (3 Trials)**

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degree tests. (Note that the yaw rate curve is uncorrected.) It is shown in this figure that good repeatability was achieved.

A first order, least squares fit was used to obtain the scale factor and bias factor between the measured yaw rate data and the derivative of the yaw position data. Starting with the first 30 degree test, a scale factor of 3.2709, and a bias factor of 0.0043 were obtained. Figure 3.7 presents these results. This figure shows that an accurate fit was obtained.

For comparison, the measured yaw position data was compared to the integral of the corrected yaw rate data. These results are also presented in Figure 3.7. Fairly good agreement was achieved.

Using the same procedure, the scale and bias factors were obtained for the remaining tests. The results are presented in Table 3.1. From the results, it was observed that the scale factor varied slightly, however a nominal value of 3.00 would not produce a great error in any of the tests. The variation in the bias was small and appeared to be random.

Based on these results, it was felt that the yaw position data was more reliable and all subsequent yaw rate data would be corrected using the same procedure.

## 2. Yaw Positioning Experiment

As discussed in the previous section, the yaw positioning experiment was used for the rate gyro calibration.

Inputs from the free gyro were used to determine the vehicle's yaw position. The position commands were given for yaw angles of (negative) 30,
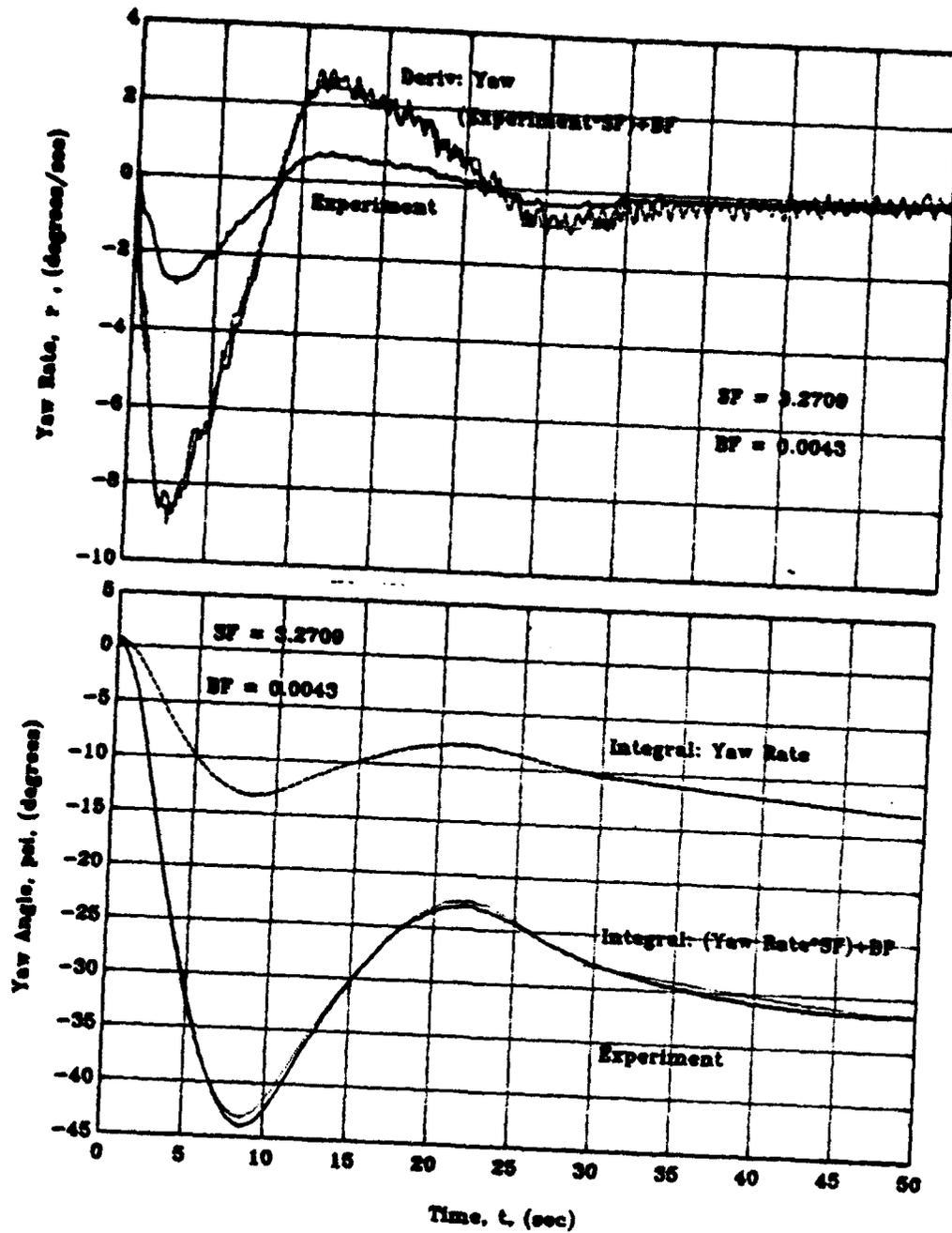
**Figure 3.7** Yaw Rate Calibration: 30 Degree Test

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**TABLE 3.1** YAW RATE CALIBRATION: SCALE AND BIAS FACTORS

| TEST | TRIAL | SCALE FACTOR (SF) | BIAS FACTOR (BF) |
|------|-------|-------------------|-------------------|
| 30 DEGREE | 1 | 3.2709 | 0.0043 |
|  | 2 | 3.2980 | 0.0055 |
|  | 3 | 3.2662 | 0.0017 |
| 60 DEGREE | 1 | 3.0059 | 0.0013 |
|  | 2 | 3.0257 | -0.0011 |
|  | 3 | 3.0209 | 0.0025 |
| 90 DEGREE | 1 | 2.9529 | 0.0004 |
|  | 2 | 2.9699 | -0.0034 |
|  | 3 | 2.9375 | 0.0010 |
| 180 DEGREE | 1 | 2.8387 | 0.0031 |
|  | 2 | 2.8592 | 0.0008 |
|  | 3 | 2.8799 | 0.0010 |
| 360 DEGREE | 1 | 2.8208 | 0.0015 |
|  | 2 | 2.8727 | 0.0004 |
|  | 3 | 2.8470 | 0.0046 |

60, 90, 180 and 360 degrees, using a proportional derivative control law. The data obtained for the calibration tests was used to analyze the yaw positioning capability of the AUV.

### 3. Lateral Positioning Experiment

The motion for the lateral positioning experiment is shown in Figure 3.8. In addition to inputs from the free gyro, inputs from the profiling sonar were used to determine the vehicle's lateral position with respect to the tank wall.

The control laws for the lateral positioning commands incorporated the combined behavior modes of yaw and lateral motion. For the yaw motion, the control effort is generated in the same way as discussed for the yaw positioning experiment. For the lateral motion however, the forward and aft lateral thrusters are used in the same direction.

$$F_{\text{Fwd Thrust (Lat)}} = F_{\text{Aft Thrust (Lat)}}$$

$$F_{\text{Thrust}} \propto V_{\text{Thrust}} |V_{\text{Thrust}}|$$

Therefore, for a linear control effort, accounting for both behavior modes, the lateral position commands for the thruster voltages are given using the *following proportional derivative control laws:*

$$V_{\text{Fwd Thrust}} = -K_{\Psi}(\Psi - \Psi_{\text{com}}) - K_r(r - r_{\text{com}}) - K_Y(Y - Y_{\text{com}}) - K_v(\dot{Y} - \dot{Y}_{\text{com}})$$

$$V_{\text{Aft Thrust}} = K_{\Psi}(\Psi - \Psi_{\text{com}}) + K_r(r - r_{\text{com}}) - K_Y(Y - Y_{\text{com}}) - K_v(\dot{Y} - \dot{Y}_{\text{com}})$$

$$K_r = K_{\Psi} \times T_{d\Psi}$$

$$K_v = K_Y \times T_{dY}$$
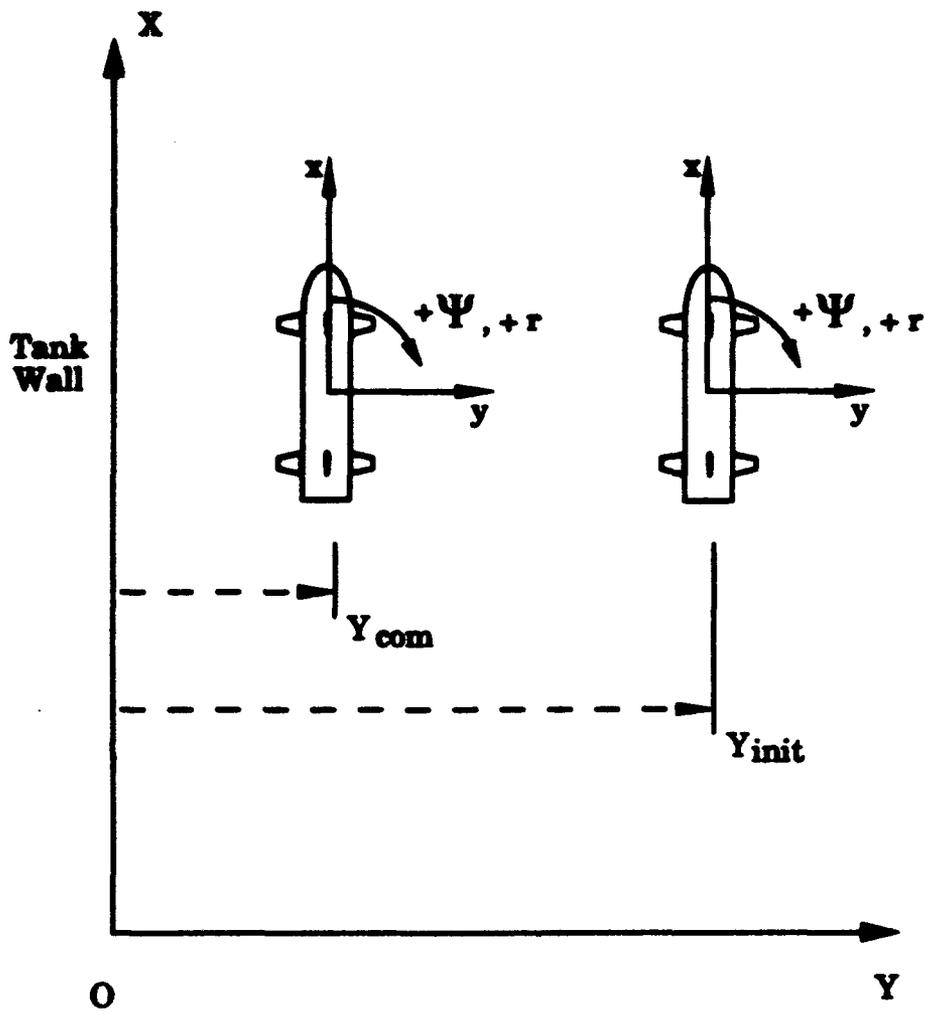
**Figure 3.6** Lateral Positioning Experiment

Table 3.2 lists the test conditions for the lateral positioning experiment. The control law gains were varied in order to examine the coupling effects between the lateral and yaw motions. The effects of changes in the range of motion were examined by varying the initial and commanded positions to cover small and large changes in position. A commanded yaw position of zero degrees was given for all tests.

Data collected included range (global Y direction) to the wall, sway velocity, yaw position, yaw rate, and forward and aft thruster voltage as functions of time.

The sway velocity data was obtained by extracting an estimate of the derivative of the lateral range data from the sonar, using a Kalman filter subprogram. The smooth velocity estimate was used for the velocity error feedback. The filter also provided a smooth position estimate which was used for the position error feedback. The subprogram for the Kalman filter, in C source code, is provide in Appendix F.

### 4. Longitudinal Positioning Experiment

The motion for the longitudinal positioning experiment is shown in Figure 3.9. In addition to inputs from the free gyro, inputs from the profiling sonar were used to determine the vehicle's position with respect to the tank wall, ahead.

The control laws for the longitudinal positioning commands account for the behavior modes of yaw and longitudinal motion, however these modes are controlled separately through use of the thrusters and the stern propulsion

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## TABLE 3.2 LATERAL AND LONGITUDINAL POSITIONING EXPERIMENTS: TEST CONDITIONS

### LATERAL POSITIONING EXPERIMENT: TEST CONDITIONS

| TEST | Ky | Tdy | Kpsi | Tdpsi | Yinit | Ycom | PSIcom |
|------|-----|-----|------|-------|-------|------|--------|
| 1 | 7 | 2 | 60 | 1 | 5.0 | 3.5 | 0.0 |
| 2 | 10 | 3 | 80 | 1 | 9.4 | 4.0 | 0.0 |
| 3 | 12 | 3 | 80 | 1 | 9.0 | 4.0 | 0.0 |
| 4 | 12 | 3 | 60 | 1 | 9.0 | 3.0 | 0.0 |
| 5 | 10 | 3 | 80 | 1 | 16.0 | 4.0 | 0.0 |

### LONGITUDINAL POSITIONING EXPERIMENT: TEST CONDITIONS

| TEST | SONAR GAIN | Kx | Tdx | Kpsi | Tdpsi | Xinit | Xcom | PSIcom |
|------|------------|-----|-----|------|-------|-------|------|--------|
| 1 | 13 | 10 | 3 | 60 | 1 | 12.0 | 7.5 | 0.0 |
| 2 | 13 | 10 | 3 | 60 | 1 | 12.0 | 5.0 | 0.0 |
| 3 | 9 | 10 | 3 | 60 | 1 | 12.0 | 5.0 | 0.0 |
| 4 | 5 | 10 | 3 | 60 | 1 | 12.0 | 5.0 | 0.0 |
| 5 | 5 | 10 | 3 | 60 | 1 | 11.6 | 5.0 | 0.0 |
| 6 | 5 | 10 | 4 | 60 | 1 | 7.0 | 2.5 | 0.0 |
| 7 | 5 | 10 | 4 | 60 | 1 | 12.0 | 3.0 | 0.0 |

43
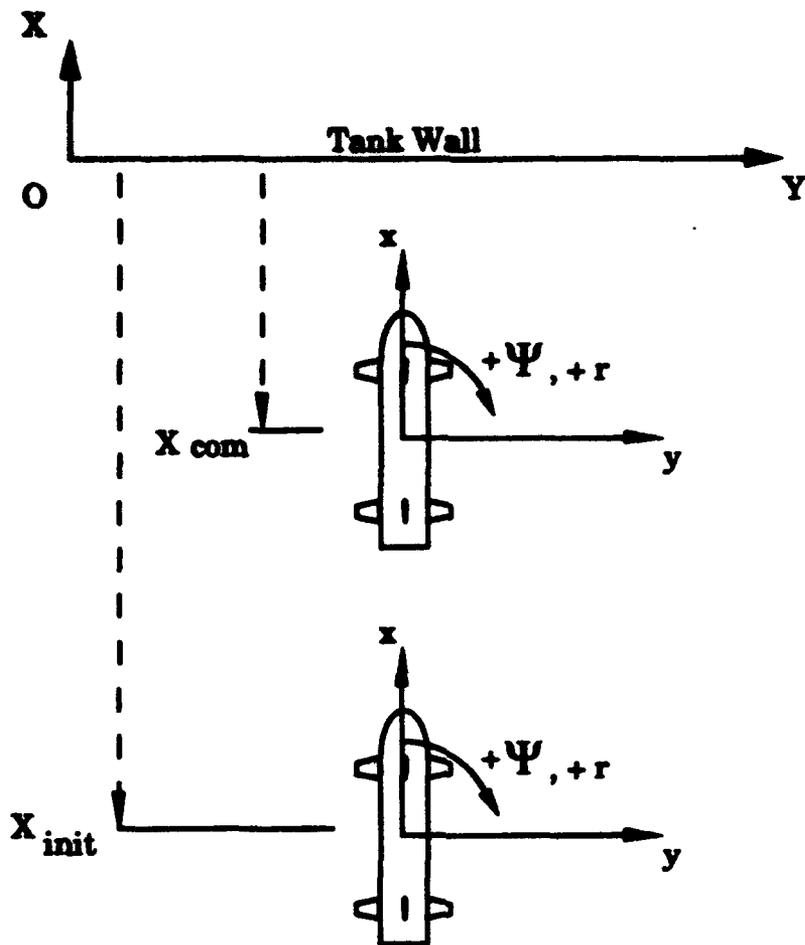
**Figure 3.9    Longitudinal Positioning Experiment**

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motors. Similar to the thrusters for lateral motion, the stern propulsion motors are used in the same direction.

$$F_{Port Prop} = F_{Stbd Prop}$$

$$F_{Prop} \propto V_{Prop}|V_{Prop}|$$

Therefore, a linear control effort is achieved, by generating the longitudinal position commands using the following proportional derivative control law for the stern propulsion motor voltages:

$$V_{Stern Prop} = K_X(X - X_{com}) + K_u(\dot{X} - \ddot{X}_{com})$$

$$K_u = K_X \times T_{dX}$$

In addition, as for the yaw positioning experiment, position commands for thruster voltages were given using the following control laws:

$$V_{Fwd Thrust} = -K_{\Psi}(\Psi - \Psi_{com}) - K_r(r - r_{com})$$

$$V_{Aft Thrust} = K_{\Psi}(\Psi - \Psi_{com}) + K_r(r - r_{com})$$

$$K_r = K_{\Psi} \times T_{d\Psi}$$

Table 3.2 lists the test conditions for the longitudinal positioning experiment. The sonar gains were varied in order to examine the effects on the stability of the position data. The sonar gains shown are equivalent to the percentages of the total transmission power of the transducer. The thruster voltage control law gains for yaw position were set at 60 and one (proportional and derivative, respectively), and a commanded position of zero degrees was given.

The lateral and yaw motion coupling effects were examined along with the effects of changes in the range of motion.

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Data collected included range (global X direction) to the wall, surge velocity, yaw position, yaw rate, and forward and aft thruster, as well as stern propulsion motor voltages as functions of time.

The surge velocity data was obtained, similarly to the lateral positioning experiment, through the use of the Kalman filter subprogram.

# IV. EXPERIMENTAL RESULTS

The purpose of this chapter is to document trends in the experimental data collected for the AUV positioning experiments. Each type of motion studied (yaw, lateral and longitudinal), is addressed separately, and specific observations are made with respect to the dynamics of the motion, ability to achieve the commanded final position, commanded thruster and stern propulsion voltages and where applicable, the effects of changes in control law gains, sonar gains and the range of motion.

The results of the positioning experiments are then compared to a theoretical model.

## A. YAW POSITIONING EXPERIMENT

As described in Chapter III, yaw positioning experiments were used for the rate gyro calibration. Inputs from the free gyro were used to determine the vehicle's yaw position. Position commands were given using proportional derivative control laws, for thruster voltages. The position commands were given for yaw angles of (negative) 30, 60, 90, 180 and 360 degrees (relative to a starting position).

The data obtained for the calibration tests was used to analyze the yaw positioning capability of the AUV. The data recorded included yaw position, yaw rate and forward and aft thruster voltage inputs as functions of time.

Figure 4.1 shows the yaw position, yaw rate and thruster voltages for the 90 degree test. The yaw position curve shows the motion response expected from a proportional derivative control law. During the initial stage of motion, the vehicle did not quite reach a constant turning rate as seen by an inflection point at approximately six seconds. With a steady state error band of approximately seven degrees, a single overshoot is observed due to inertial forces initially dominating the motion. Drag forces, proportional to the square of the yaw rate then became dominant, and the motion of the vehicle was heavily damped to an accurate steady state position.

The yaw rate curve shows consistent results with peak turning rates occurring at approximately six and 13.5 seconds.

The thruster voltage curve shows the forward and aft thrusters were employed in equal and opposite directions. Also note that saturation had occurred until approximately six seconds, which as previously mentioned, was not long enough to reach a constant turning rate.

The effects of the magnitude of the commanded turn are shown in Figure 4.2. The yaw position curves show that the vehicle had reached a constant, peak turning rate at approximately seven seconds, for the 180 and 360 degree tests. Consistent dynamic results are shown with single overshoots followed by heavily damped approaches to accurate steady state positions.

The yaw rate curves show the constant turning rates for the 180 and 360 degree tests. The differences in the values of the rates is due to experimental repeatability. The average peak turning rate was observed to be approximately 16.0 degrees per second.

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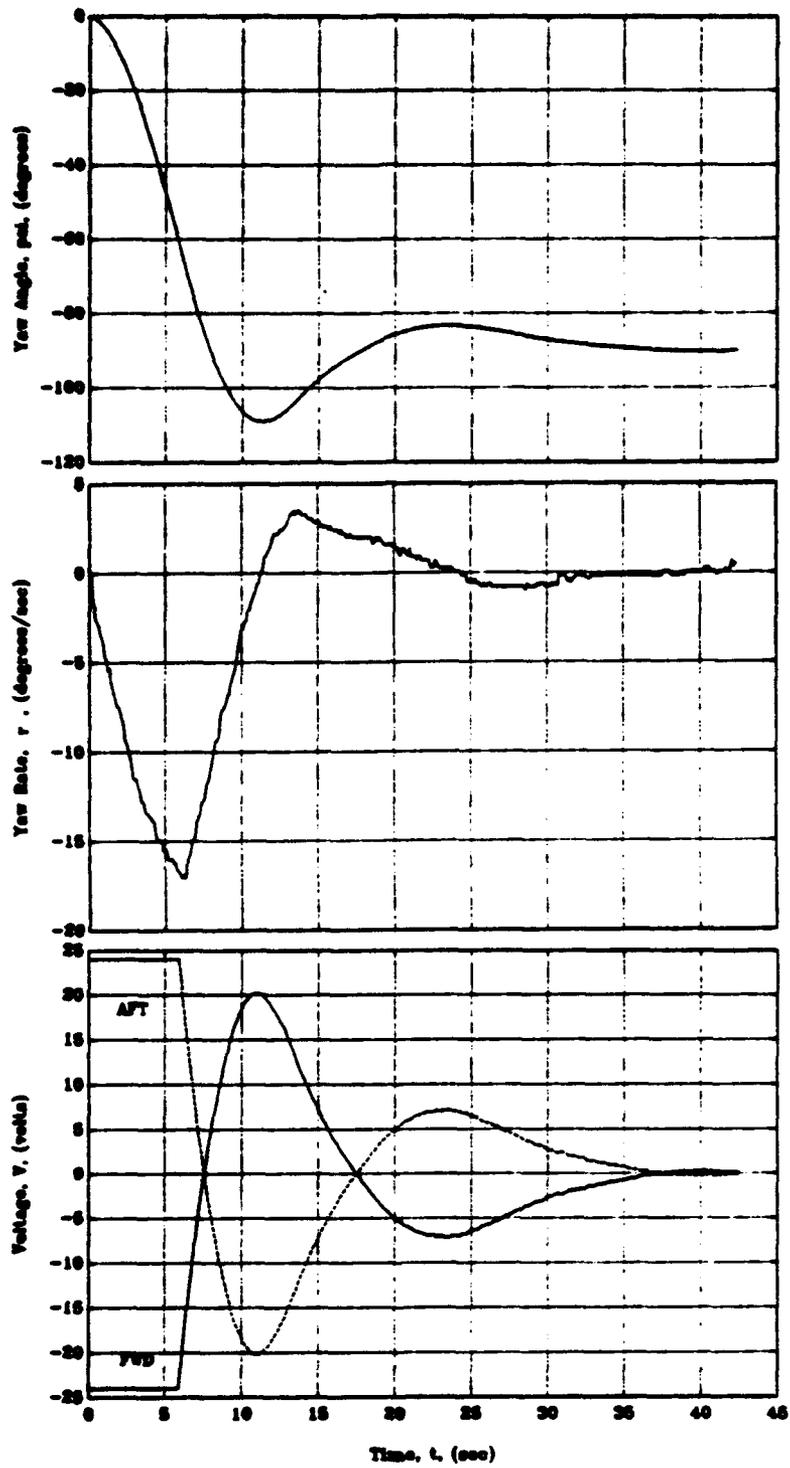
**Figure 4.1   Yaw Position Experiment: 90 Degree Test**

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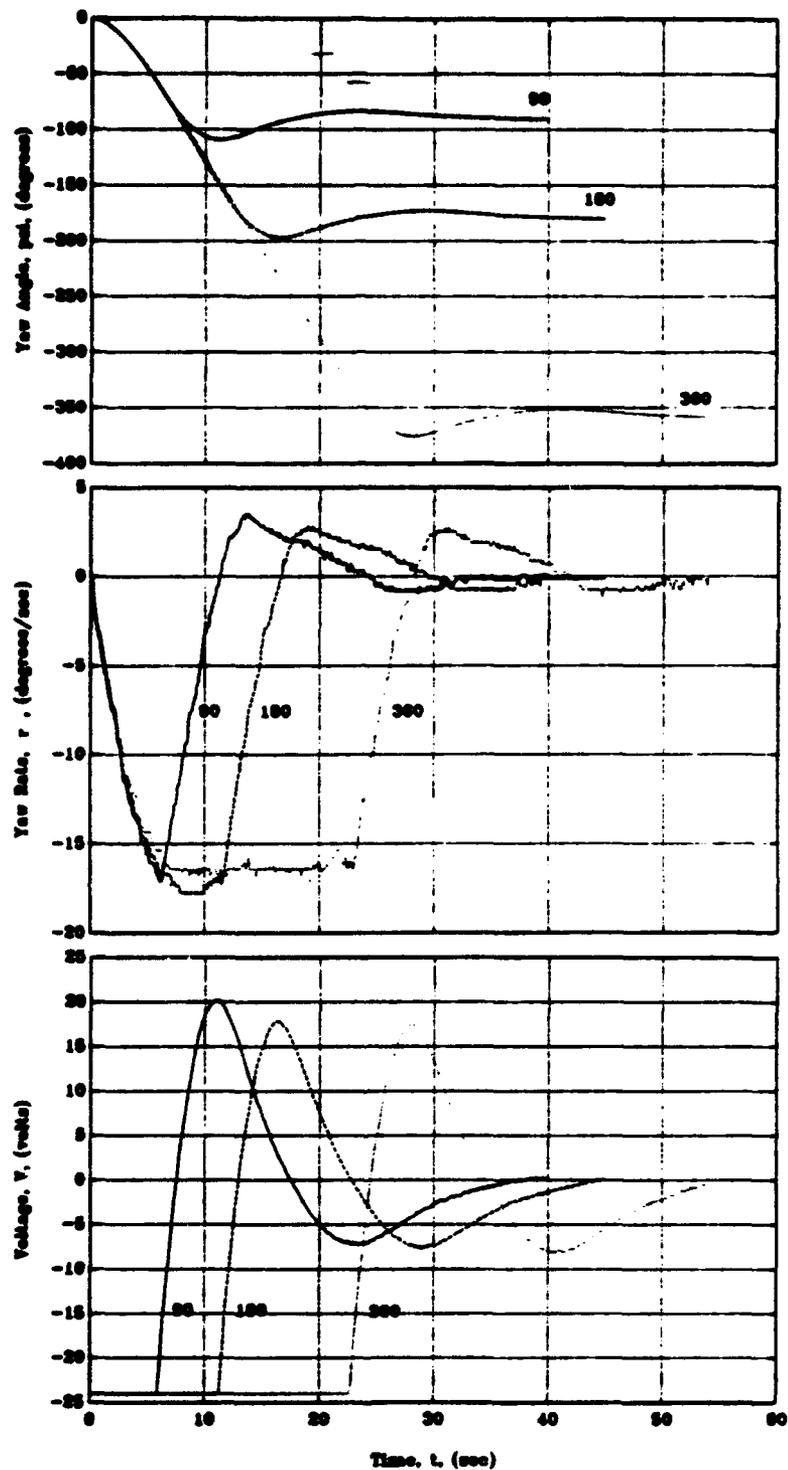
**Figure 4.2** Yaw Position Experiment: 90, 180 and 360 Degree Tests

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While the error is small, the final steady state yaw position was not exact in all cases. As discussed in Cody (1992), a small voltage threshold exists for the thruster motors, due to mechanical friction in the motor and reduction gear housing (stiction), which prevents very small corrections in position. This condition, to varying extents exists in all of the thruster assemblies as well as the stern propulsion assemblies.

The thruster voltage curves show the different time periods of saturation for the three tests. The differences in the peak voltages are due to the differences in the combined effects of the position error and the turning rate from which the proportional derivative control law determines the control effort. As previously mentioned, the final steady state voltage was not always zero volts due to thruster stiction.

The vehicle's ability to recover a commanded position, given a disturbance is shown in Figure 4.3. Once the vehicle reached the commanded position, it was given two manual disturbances in the direction of the overshoot. In both cases, the commanded position was quickly recovered. The thruster curve shows that saturation occurred for both recovery efforts.
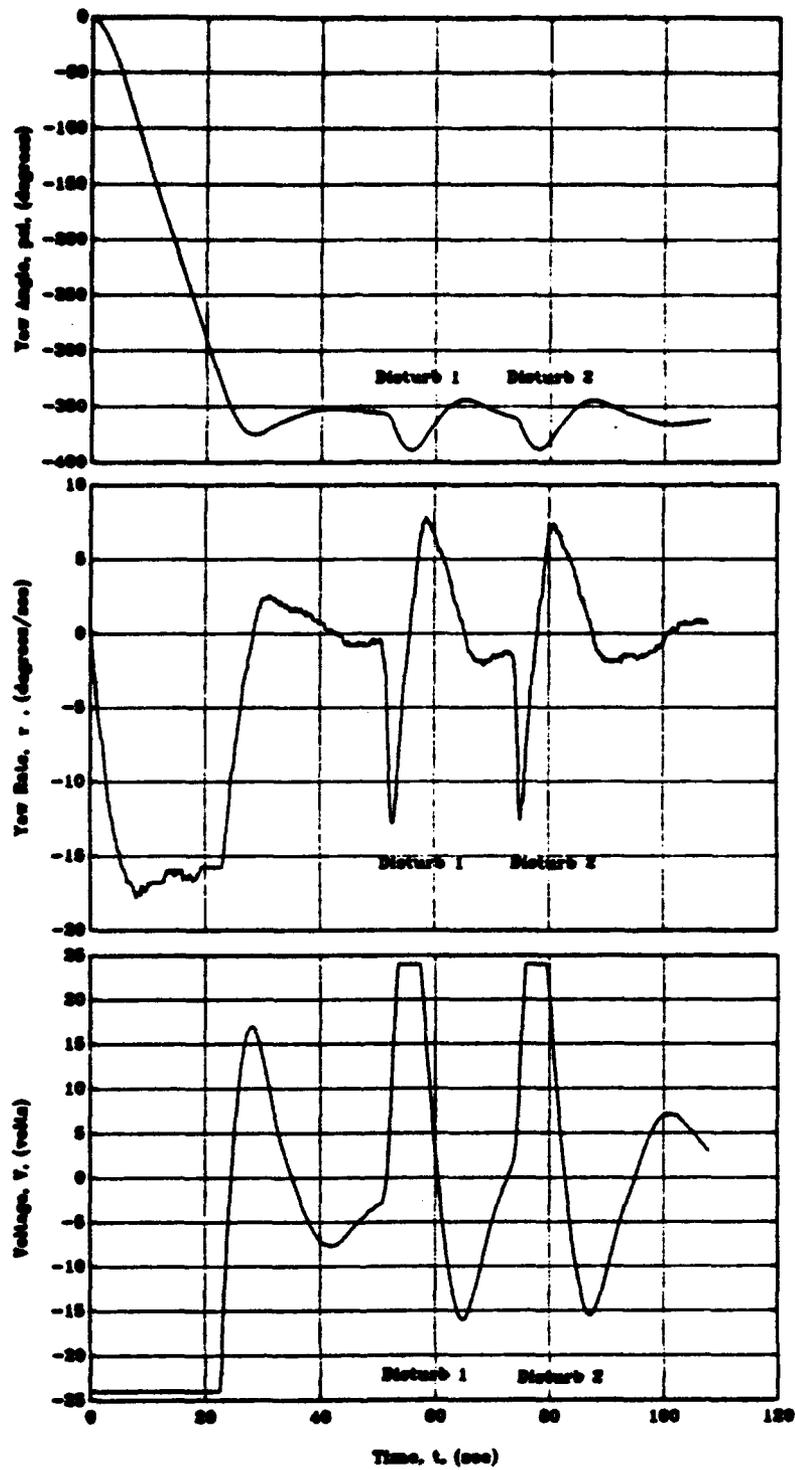
**Figure 4.3** Yaw Position Experiment: 360 Degree Test, with Disturbances

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## B. LATERAL POSITIONING EXPERIMENT

The procedure for the lateral positioning experiment was described in Chapter III. Inputs from the free gyro and the profiling sonar were used to determine the vehicle's lateral position with respect to the tank wall. Position commands for the thruster voltages were given using proportional derivative control laws.

The test conditions for the lateral positioning experiment are shown in Table 3.2. The data collected included range (global Y direction) to the wall, sway velocity, yaw position, yaw rate, and forward and aft thruster voltage as functions of time.

Figure 4.4 shows the results for Test 1. The range curve shows a single overshoot approach to an accurate steady state commanded position for a modest positioning command as expected for the proportional derivative control. Consistent with the results for the yaw positioning experiment, error in the final steady state position achieved is due to thruster stiction. A noticeable amount of noise is present in the range signal and is emphasized in the velocity curve.

The yaw position curve shows very small deviations from the commanded zero degree position. For clarity, the negative value of the forward thruster voltage was plotted for the thruster voltage curve. Neither thruster reached saturation for this small range of motion, however the relative dominance of the yaw position error to the control effort can be seen in the difference between the voltage curves. This difference is shown in Figure 4.5, where the yaw position curve is also plotted for comparison.
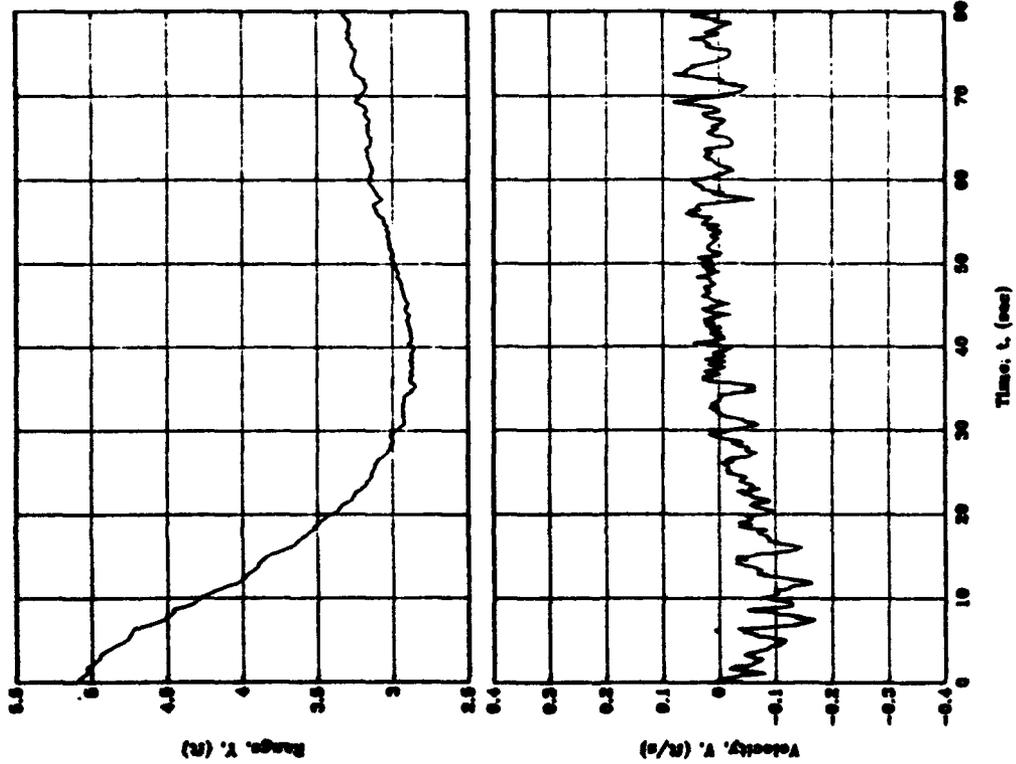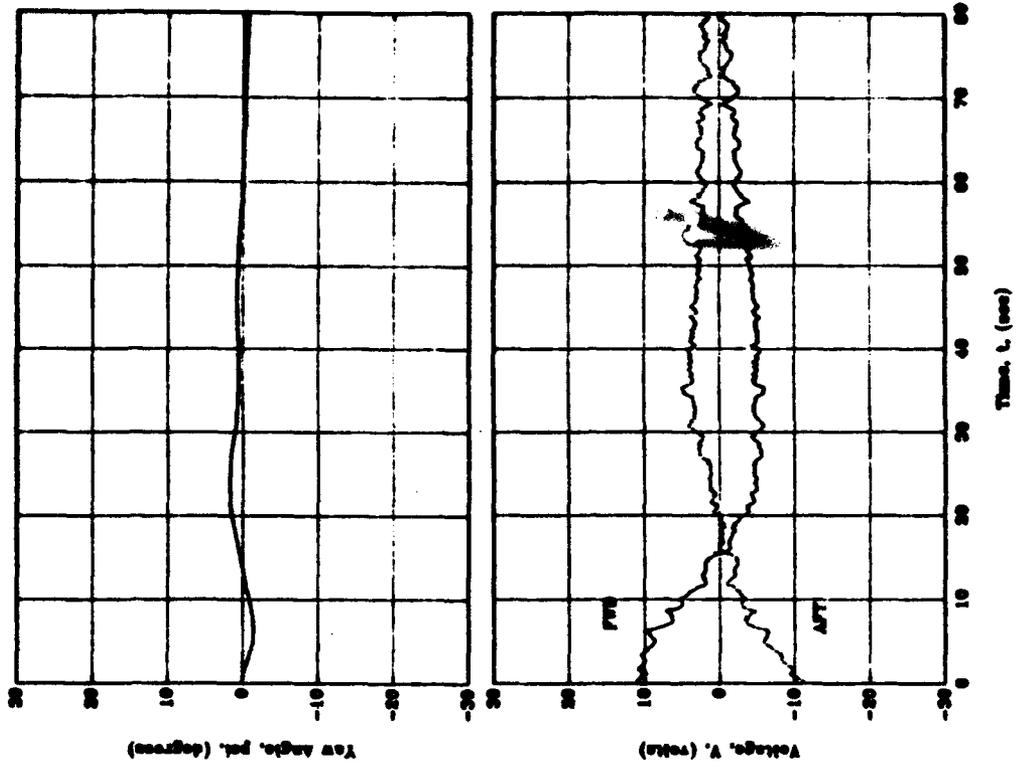
Figure 4.4  Lateral Position Experiment: Test 1

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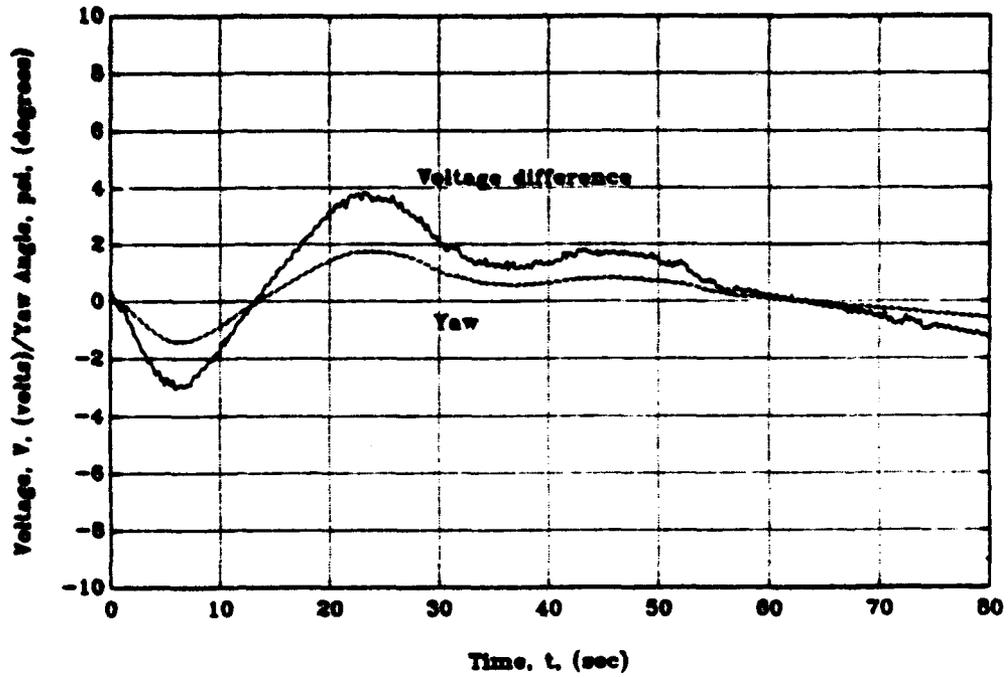
**Figure 4.5** Lateral Position Experiment: Test 1
(Thruster Voltage /Yaw Position)

For Test 2, a greater range of motion was commanded, and the control law gains were increased. The yaw position curve of Figure 4.6 shows the characteristic approach to the commanded position with slightly less noise, until 70 seconds where the sonar return went unstable. This instability at close range, was attributed to a high sonar gain. The effects of reducing the sonar gains were examined during the longitudinal positioning experiment.

With the increased control law gains, coupling of the two motion control modes of yaw and sway was emphasized, as shown by the yaw position curve. Proportional derivative control does not compensate for this effect, and the result was a disturbance effect created by one mode working against the other.

The thruster voltage curve shows that both thrusters reached saturation. The aft thruster was reduced sooner due to the decrease in yaw position caused by the smaller horizontal cross-section area of the vehicle's stern.

Further increase of the lateral position control law gains showed little reduction in the response time to achieve the commanded position in Test 3, however the yaw position was stabilized as shown in Figure 4.7.

Test 4 demonstrated that a softer vehicle response, in yaw position, resulted from reducing the yaw position control gains, as shown in Figure 4.8. In this test, greater sway induced yaw motion was developed.

A greater range of motion was attempted for Test 5, and as Figure 4.9 shows, the thrusters were saturated for a greater period of time resulting in reduced vehicle control in yaw position.
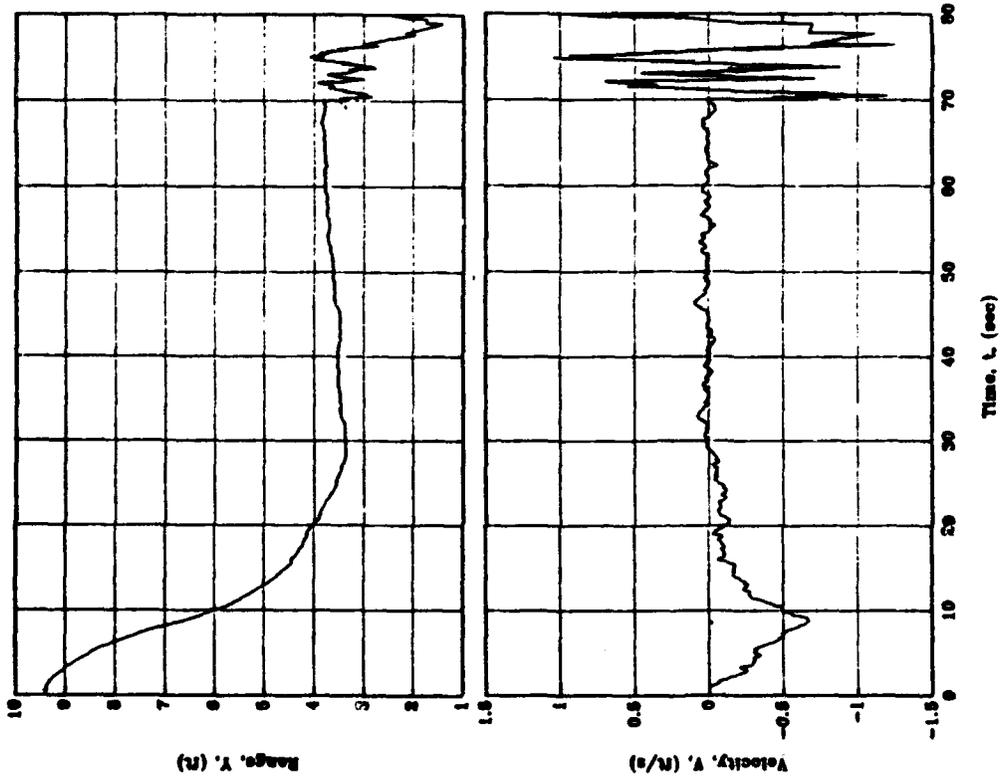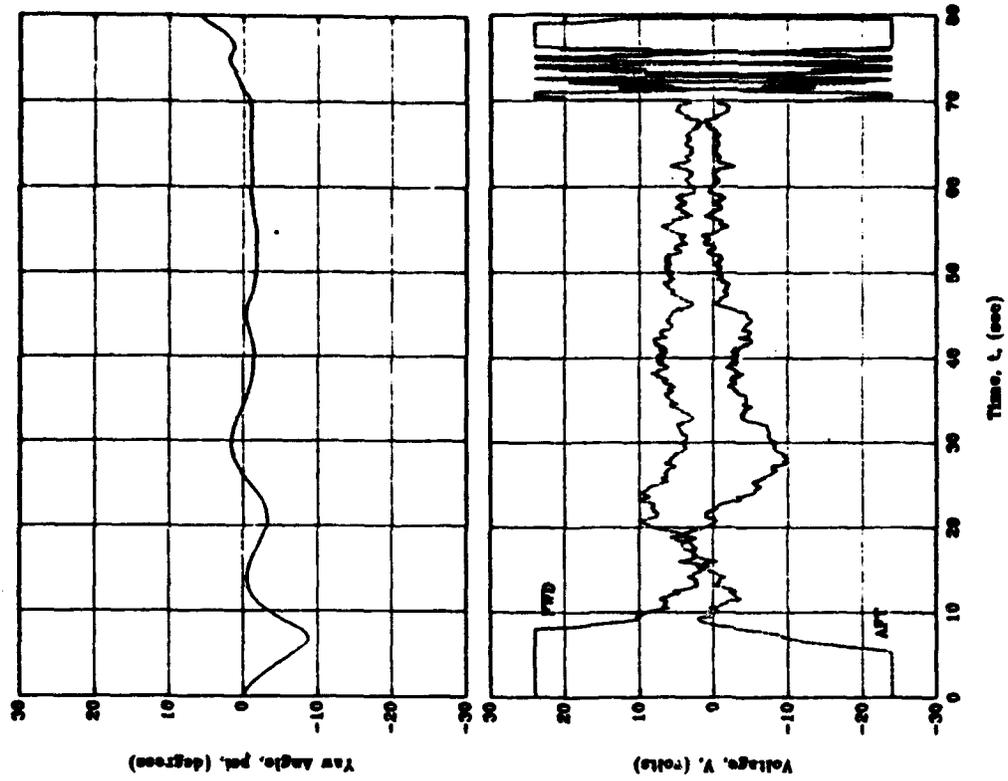
**Figure 4.6   Lateral Position Experiment: Test 2**
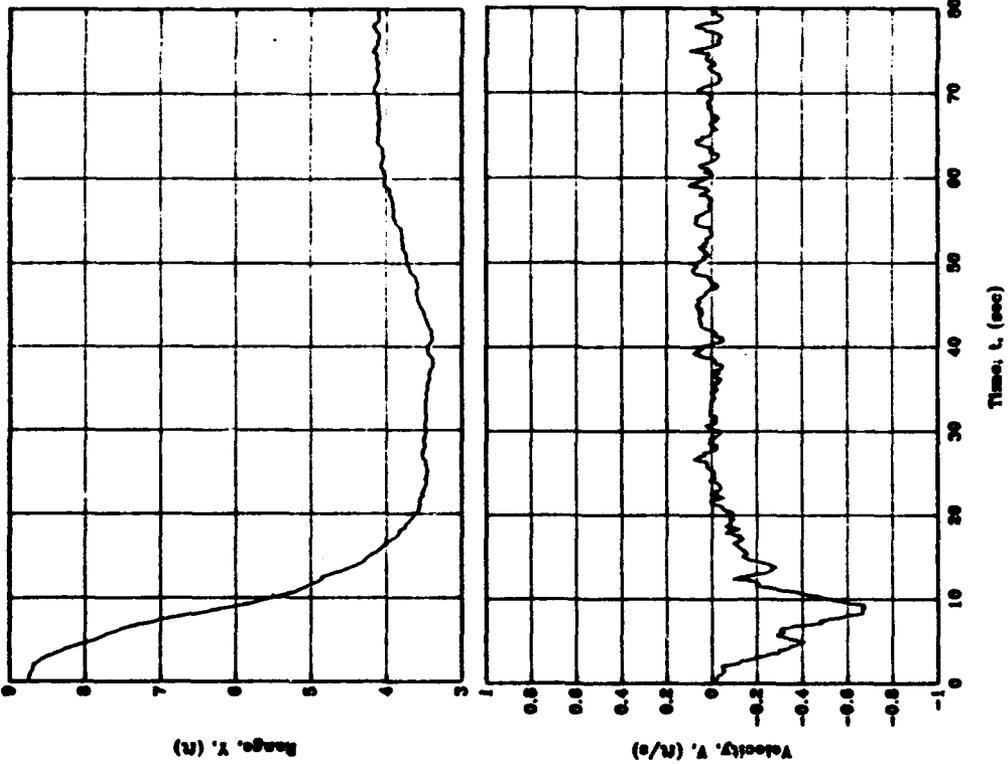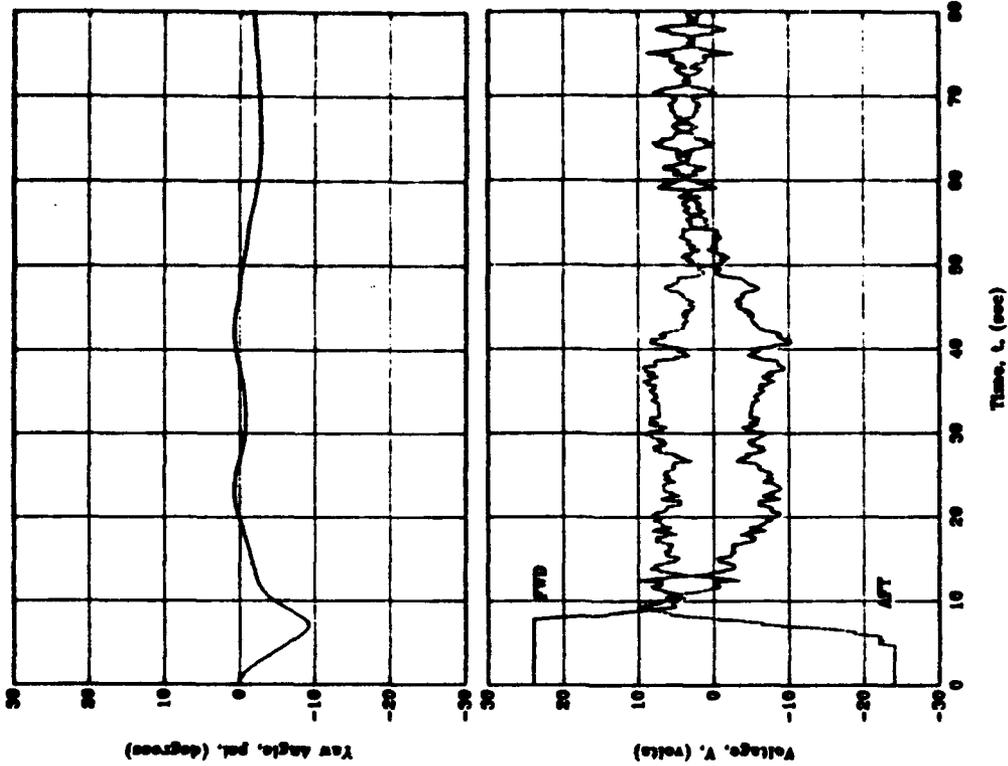
**Figure 4.7  Lateral Position Experiment: Test 3**
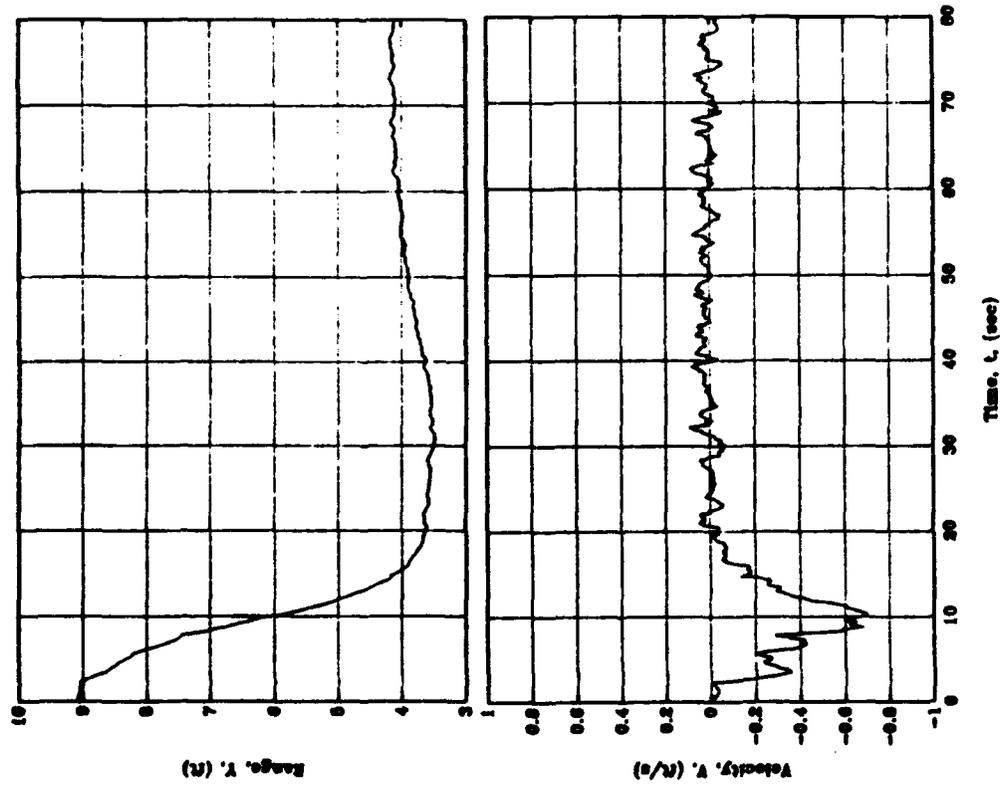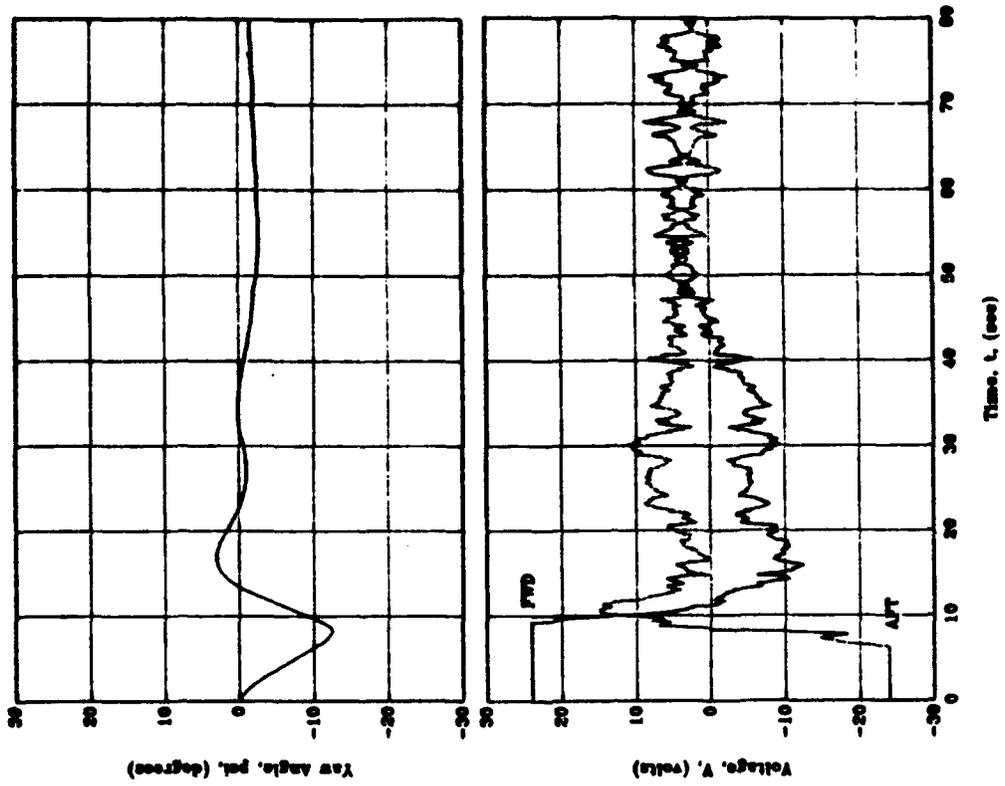
Figure 4.8   Lateral Position Experiment: Test 4
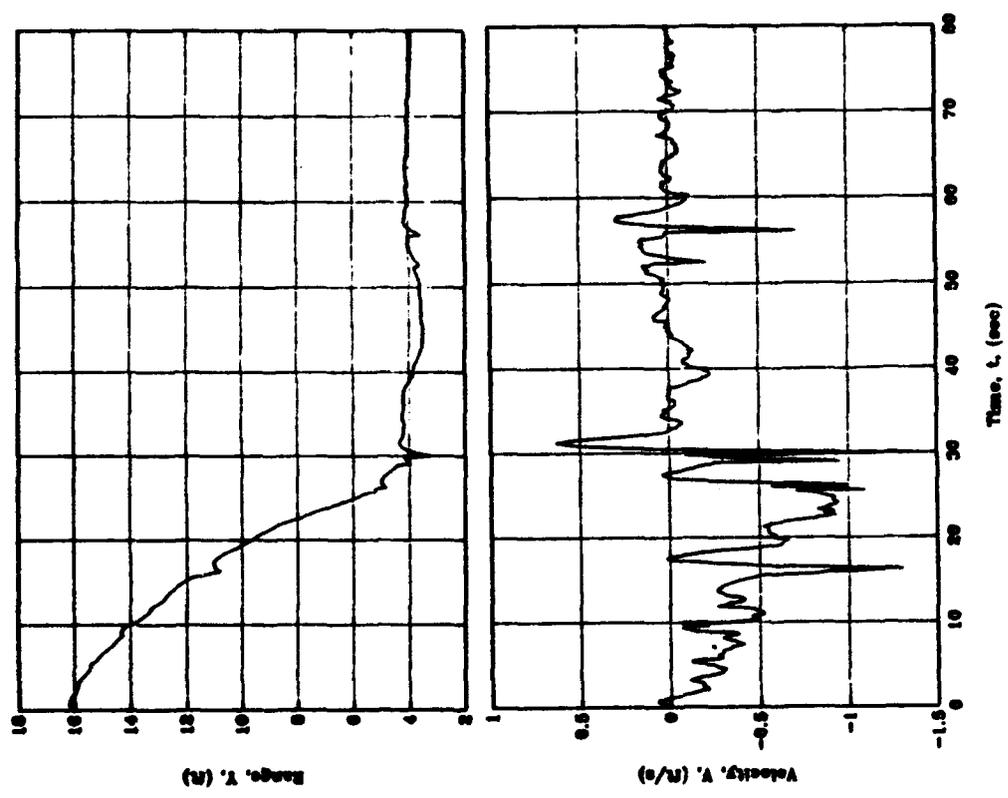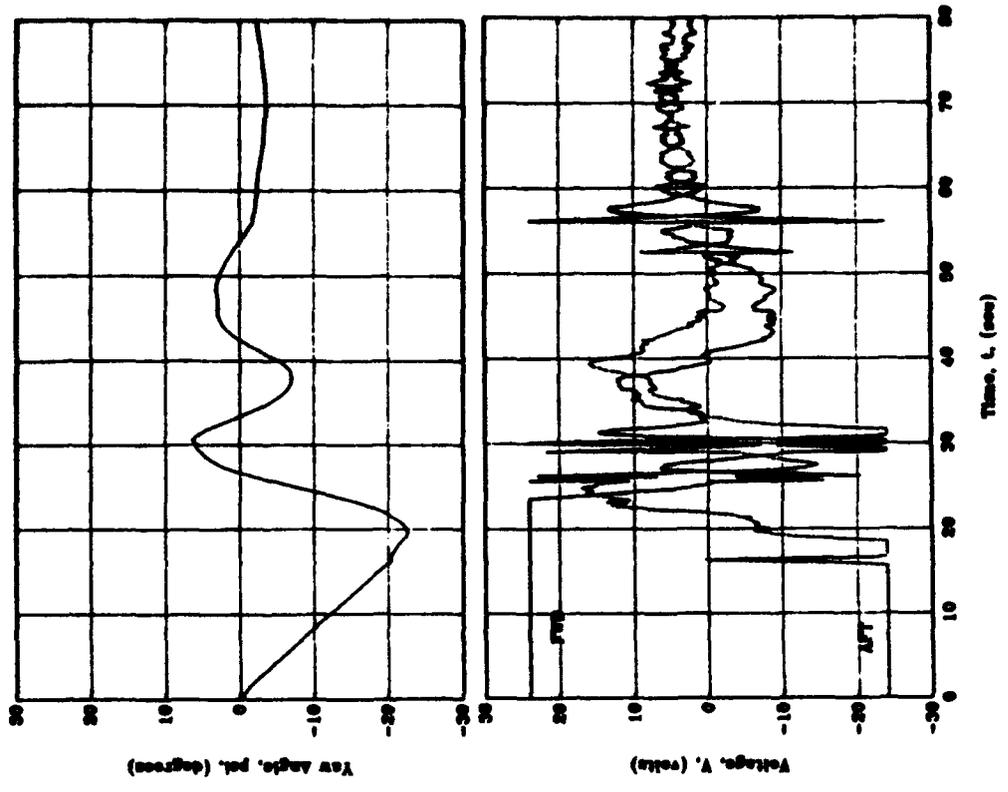
**Figure 4.9  Lateral Position Experiment: Test 5**

60

## C. LONGITUDINAL POSITIONING EXPERIMENT

Chapter III described the procedure for the longitudinal positioning experiment. Inputs from the free gyro and the profiling sonar were used to determine the vehicle's longitudinal position with respect to the tank wall. Position commands for the stern propulsion and thruster voltages were given using proportional derivative control laws.

The test conditions for the longitudinal positioning experiment are shown in Table 3.2. The data collected included range (global X direction) to the wall, surge velocity, yaw position, yaw rate, forward and aft thruster voltage and stern propulsion motor voltage as functions of time.

The dynamic characteristics of the motion for Test 1 were consistent with the proportional derivative control as shown in Figure 4.10. A single overshoot was observed, with a highly damped approach to the commanded steady state position. The stiction effects were observed in the stern propulsion assemblies, which resulted in a small steady state position error in the longitudinal position.

The velocity curve reflects a greater amount of signal noise as the sonar reaches a position closer to the wall.

The yaw position curve reflects the motion induced by the stern propulsion motors operating independently with different levels of stiction.

The thruster voltage curve shows that small thruster control efforts were generated to correct the yaw motion. Although identical voltage signals were generated for both stern propulsion motors, the negative value of the right propulsion motor was plotted for clarity. Saturation was observed for both

61
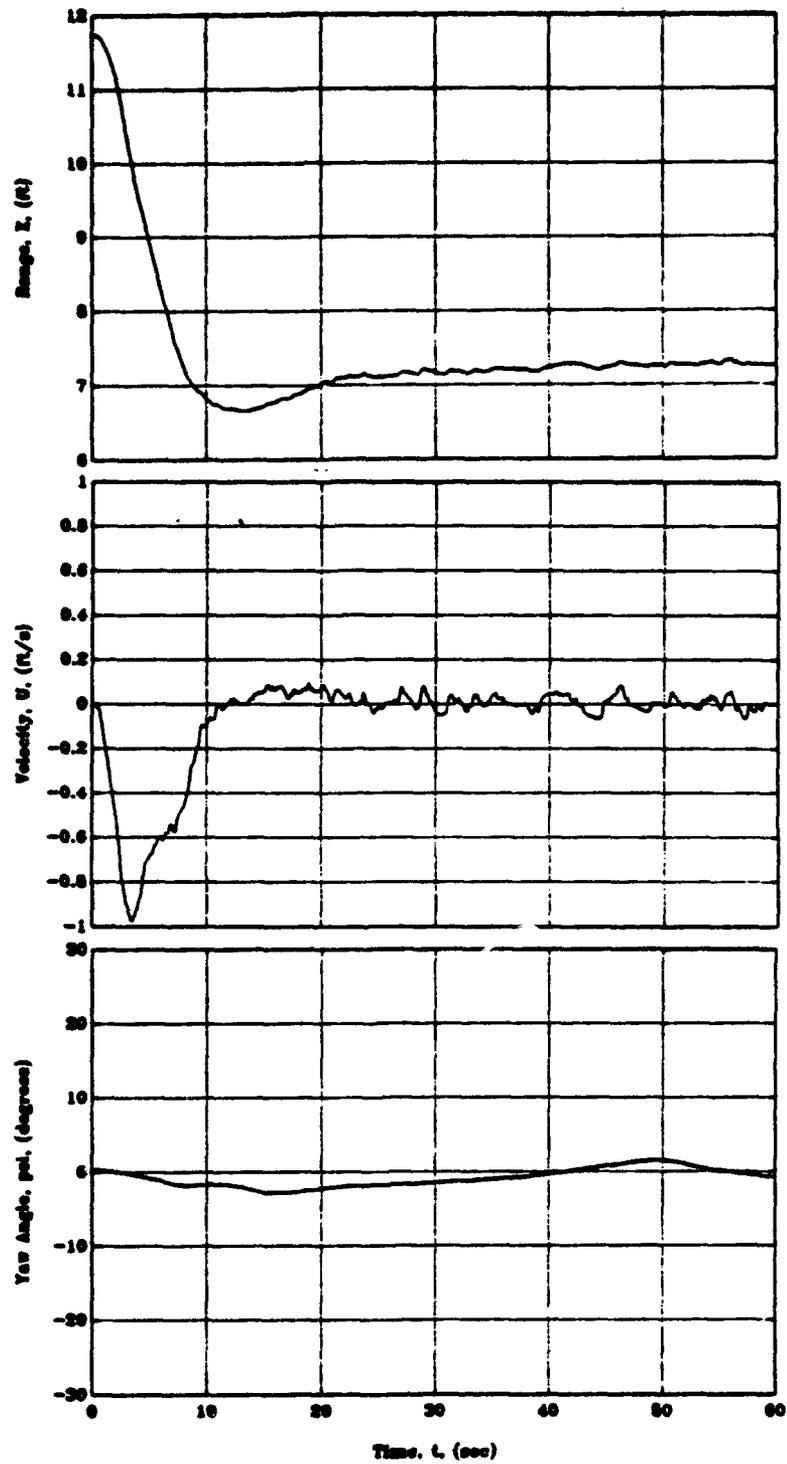
**Figure 4.10** Longitudinal Position Experiment: Test 1
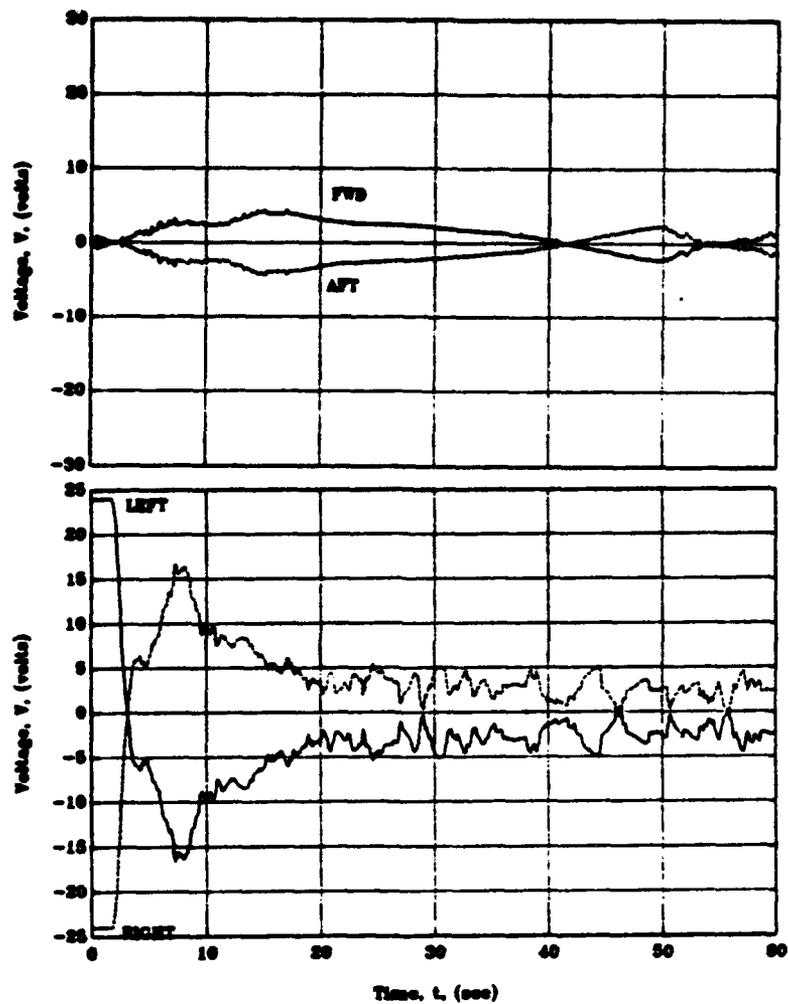
**Figure 4.10** Longitudinal Position Experiment: Test 1 (continued)

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motors followed by direction reversals to achieve the commanded steady state position.

For Test 2, a final commanded position closer to the tank wall (5.0 feet) was attempted. As shown in Figure 4.11, the stern propulsion motors were saturated for a greater period of time and a higher surge velocity was reached which resulted in greater, reversing effort.

Additionally, as the sonar spent a greater amount of time in closer proximity to the wall, the range input became unstable. This effect produced a greater amount of noise in the lateral range and surge velocity plot.

The same commanded position was attempted for Test 3, however a lower sonar gain was used (9 vice 13). Figure 4.12 shows that the same motion resulted with less noise produced in the range and velocity signals.

For Test 4, the sonar gain was reduced further (to 5), however very little improvements in the motion or the noise levels were observed, as shown in Figure 4.13.

Figure 4.14, for Test 5 demonstrates the repeatability with the same results as Test 4.

A very aggressive approach to the wall was attempted for Test 6 using a commanded position of 2.5 feet. Figure 4.15 shows that frequent voltage adjustments were generated to the stern propulsion motors which resulted in slight oscillations in longitudinal position and velocity as the vehicle approached the steady state position.
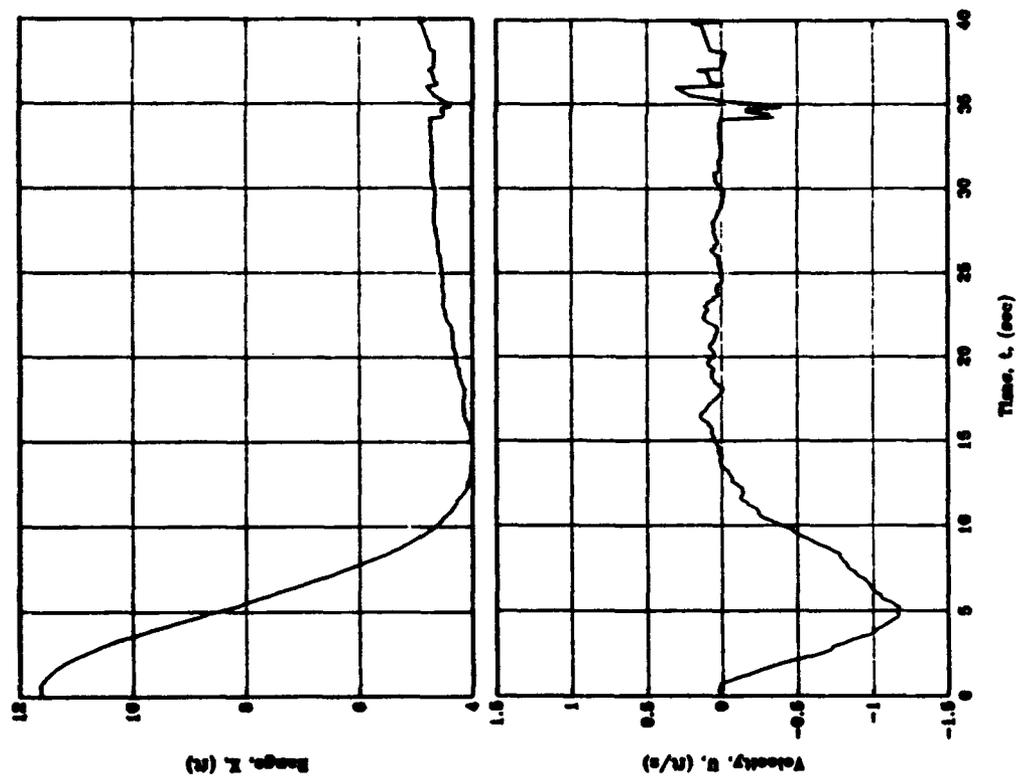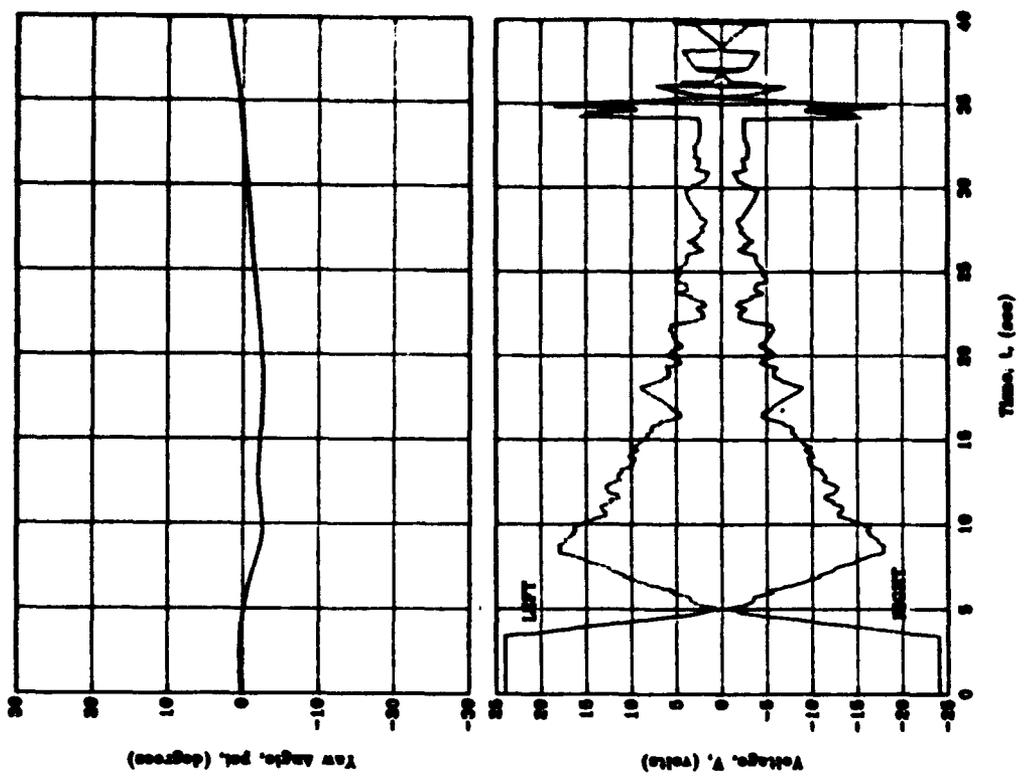
**Figure 4.11  Longitudinal Position Experiment: Test 2**

65
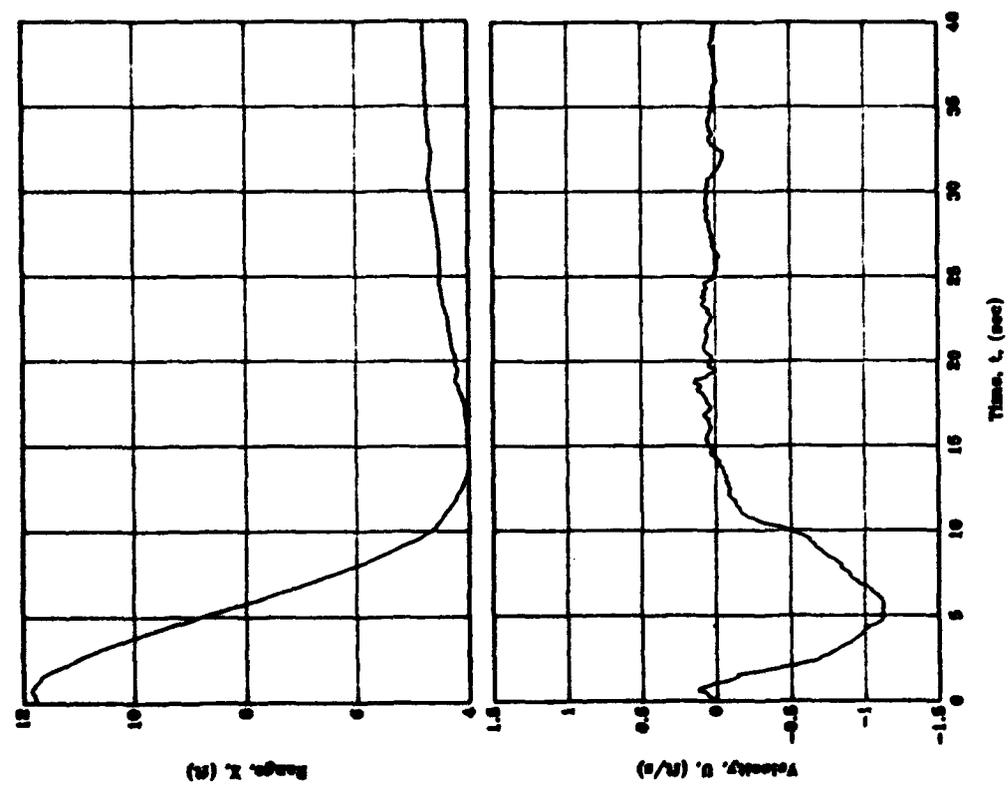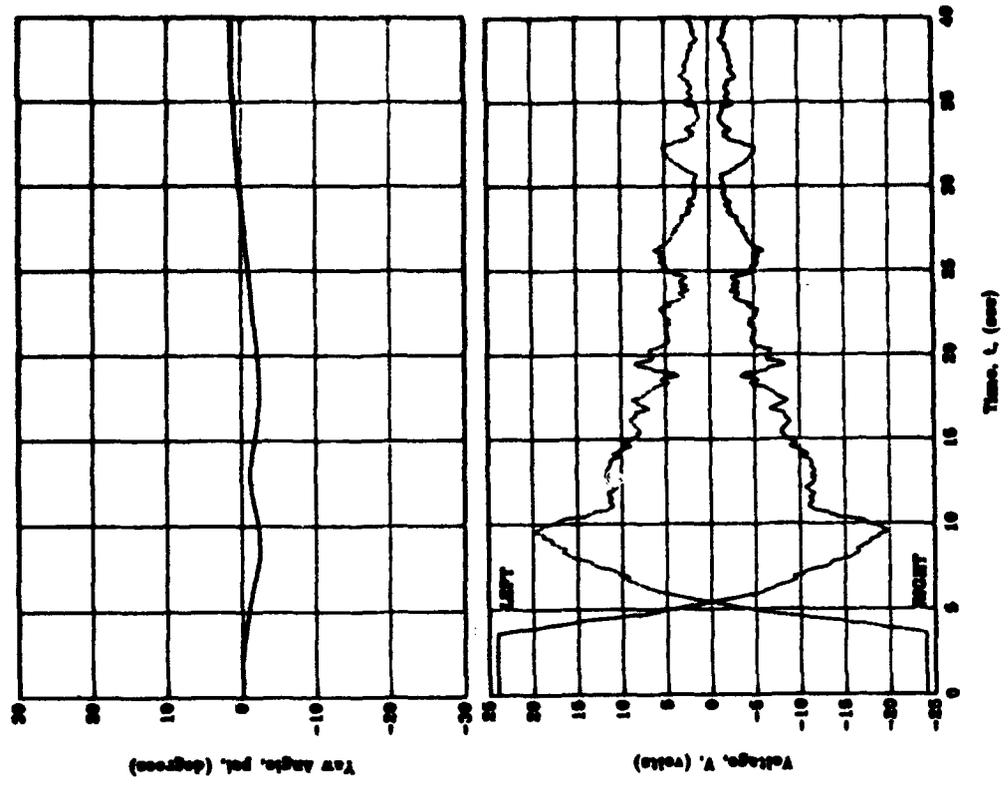
Figure 4.12 Longitudinal Position Experiment: Test 3

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Figure 4.18   Longitudinal Position Experiment: Test 4

67
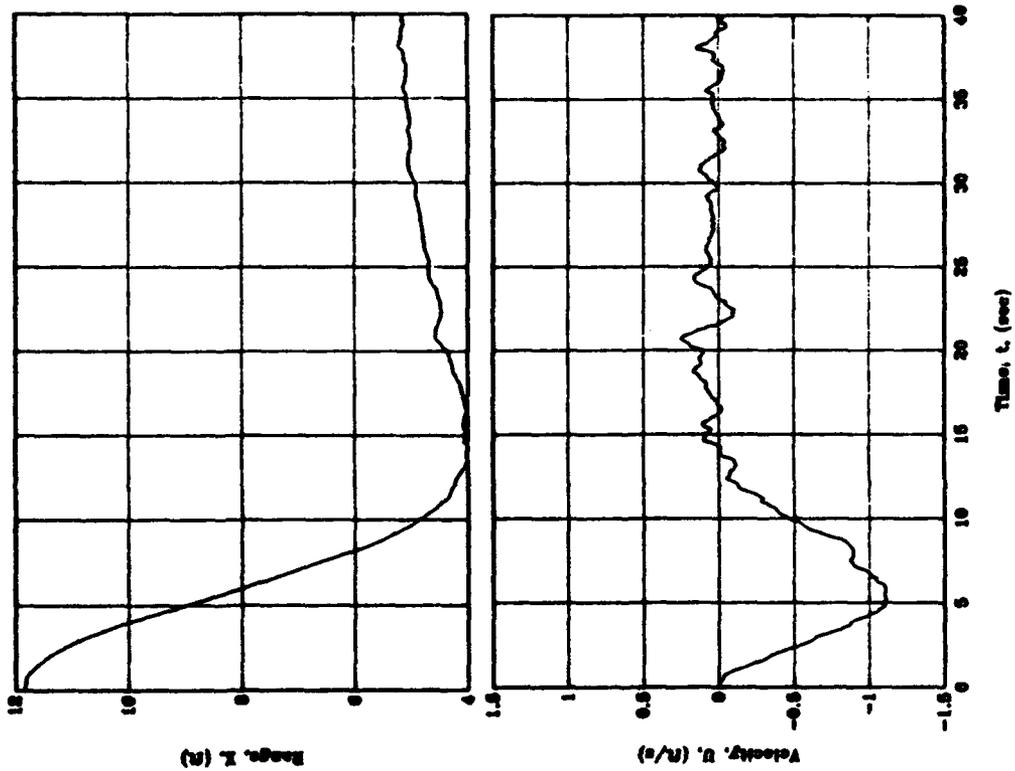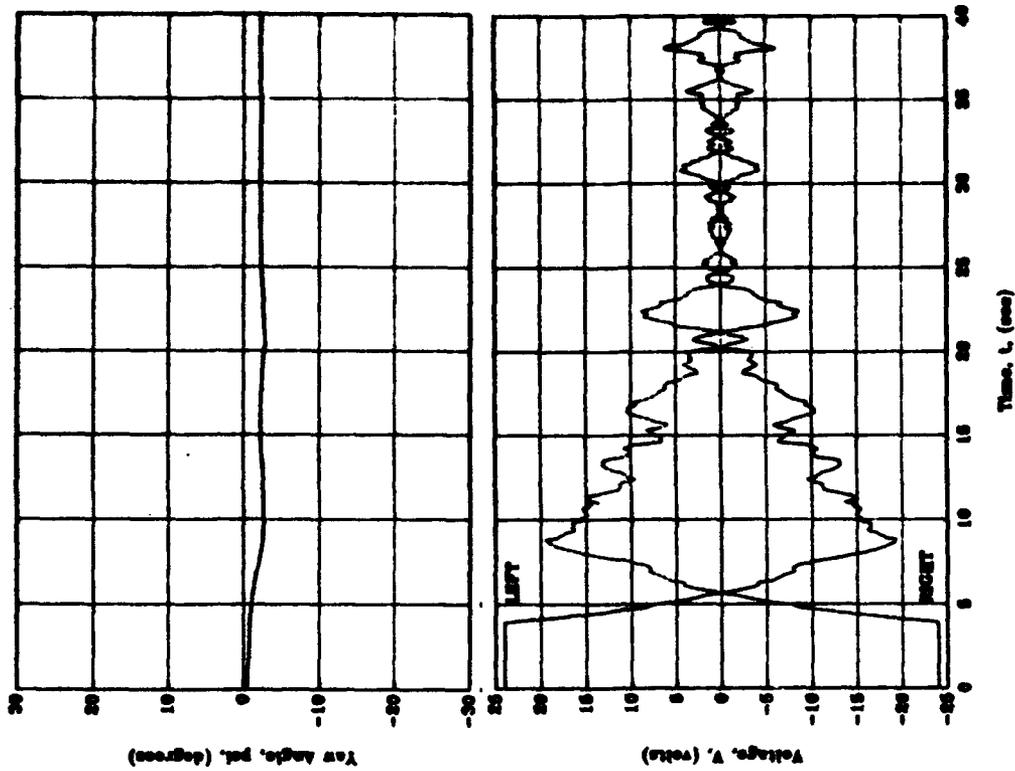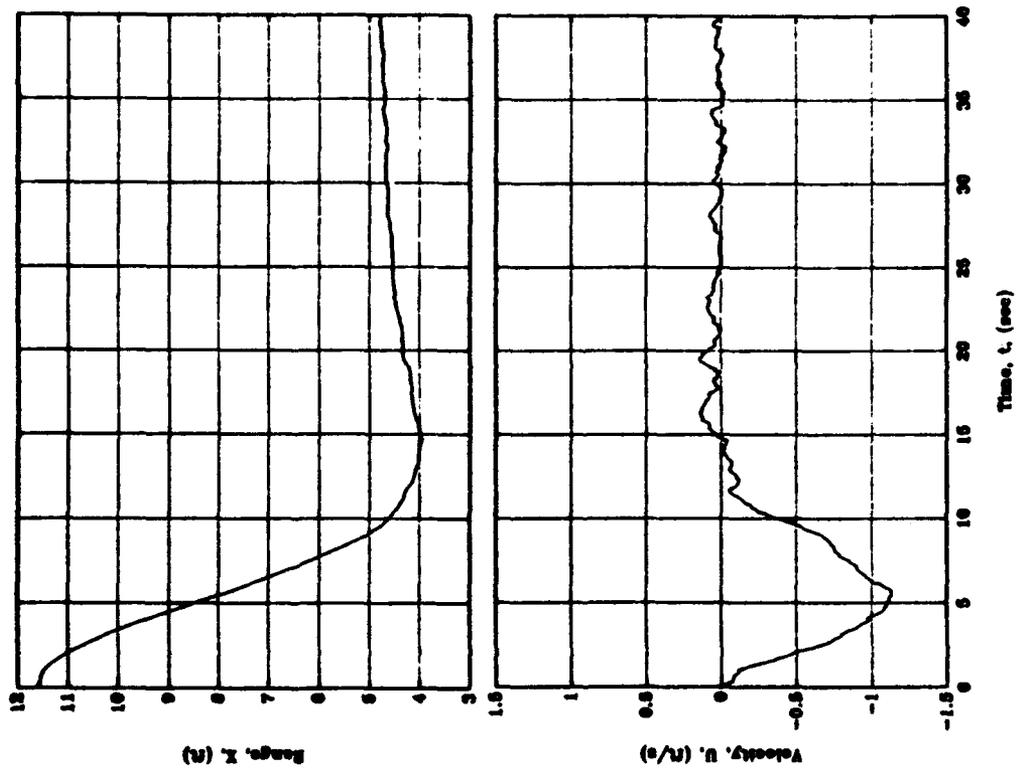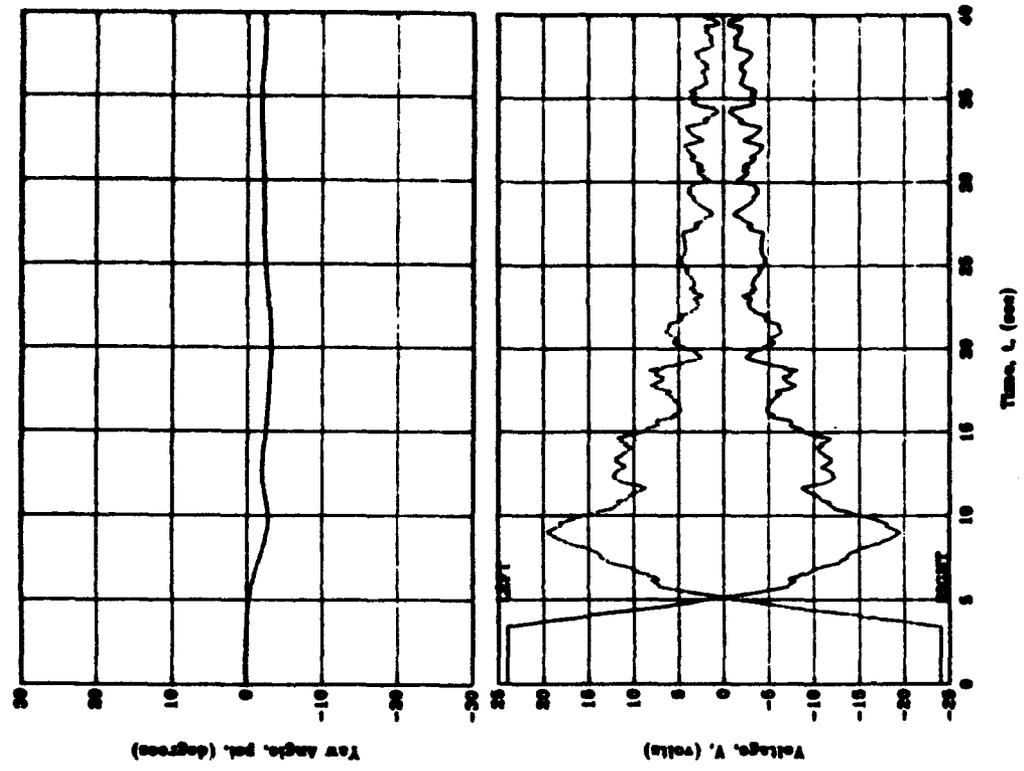
Figure 4.14   Longitudinal Position Experiment: Test 5

68
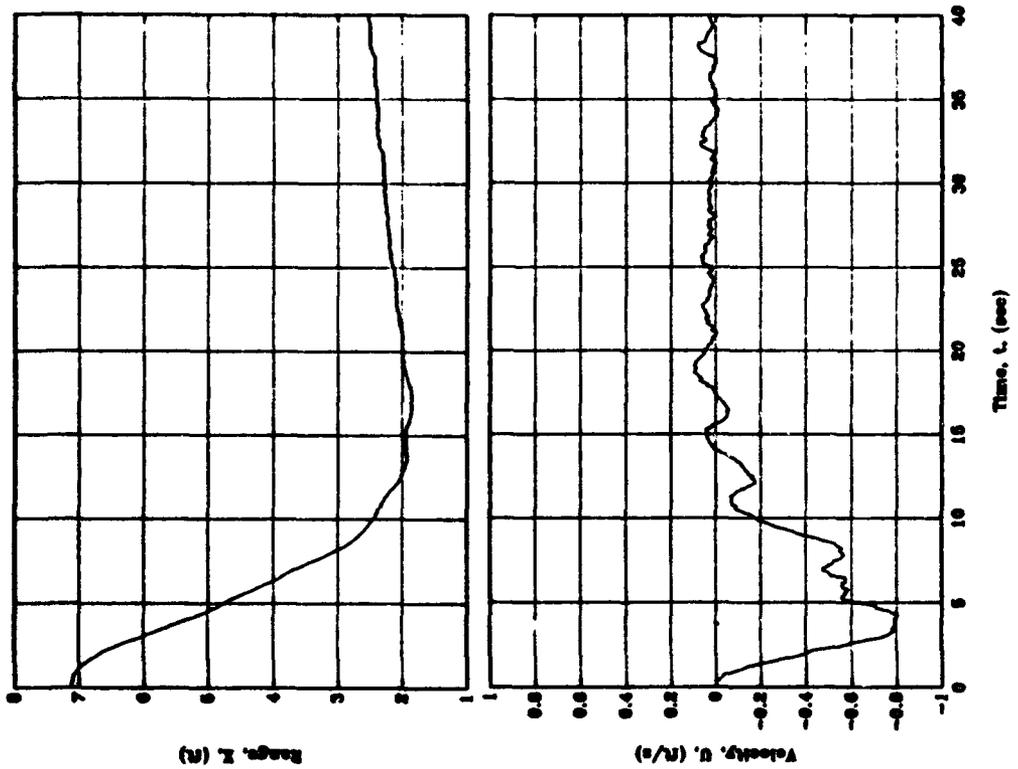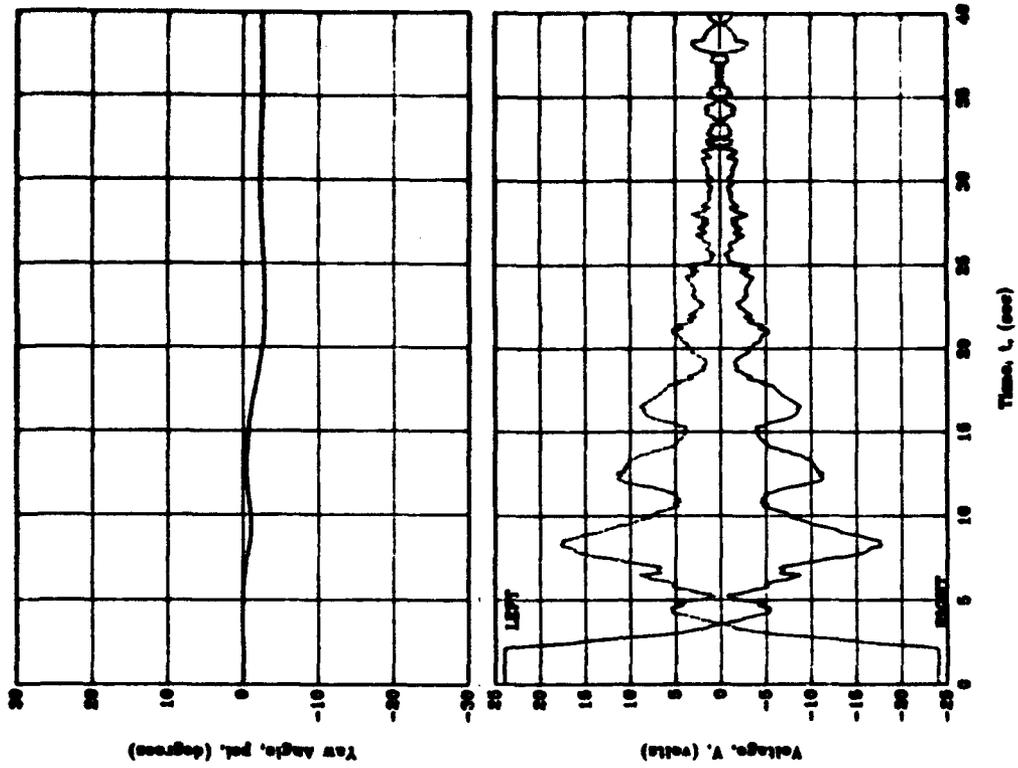
**Figure 4.15 Longitudinal Position Experiment: Test 6**

69

The largest range of motion (12.0 to 3.0 feet) was demonstrated for Test 7. Figure 4.16 shows a very good approach to the commanded steady state longitudinal position without the oscillations observed for Test 4.
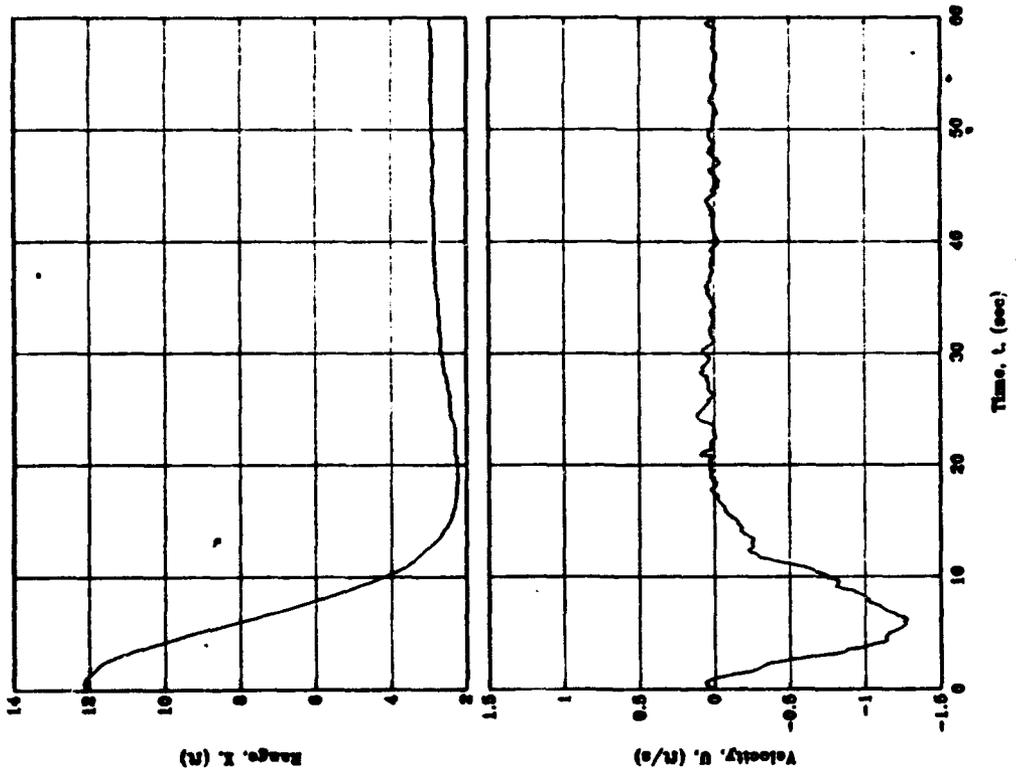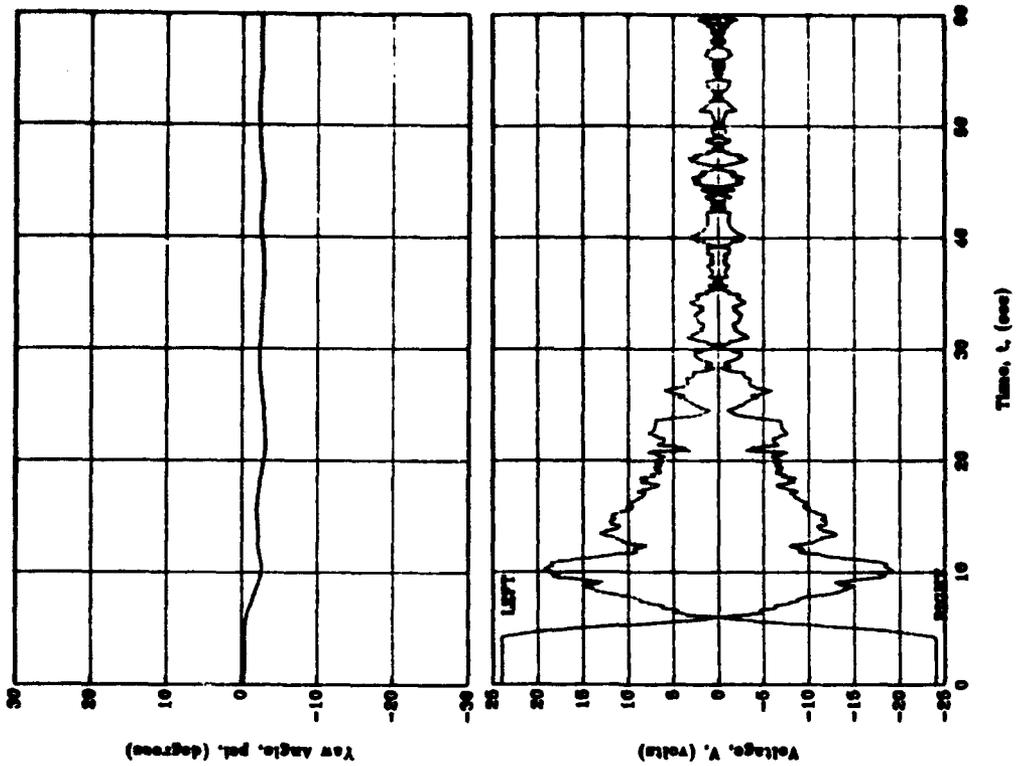
**Figure 4.16** Longitudinal Position Experiment: Test 7

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## D. THEORETICAL MODEL

This section presents a theoretical model for the horizontal plane maneuvering of the AUV, during hover conditions. The development of the model is discussed in this section along with the results, which compare the actual motions of the AUV II, determined experimentally, with those predicted by the model.

### 1. Theoretical Model Development

The purpose of developing this theoretical model of the AUV, is to provide the capability to predict its motion under various maneuvering conditions. These results provide the basis for the development of a model based control system, whereby the predicted vehicle positions, velocities and accelerations during a particular maneuver are compared to the actual vehicle motions to produce an error signal which is then used to generate a corrective control signal. The model so developed is particular to the NPS AUV II vehicle although its structure may be generalized to other vehicles if specific coefficient values for those other vehicles were determined.

For the development of the AUV model, the simplified case of horizontal plane maneuvering is considered. Table 4.1 lists the symbols and variables used in the model development. The variables used are referenced to the global and body fixed coordinate systems of Figure 3.4. Only those variables applicable to two-dimensional, horizontal plane motion are shown. A dot over a variable indicates the time derivative of that variable.

In the case of horizontal plane maneuvering, the assumption was made that the center of mass of the vehicle is below its body fixed origin (so

## TABLE 4.1  AUV MODEL: SYMBOLS AND VARIABLES

| Symbol/Variable | Description |
|---|---|
| X , Y | Distance along global coordinate axis |
| x , y | Distance along body fixed coordinate axis |
| u , v | Velocity component (surge, sway) along body fixed coordinate (x, y) axis |
| r | Angular velocity component (yaw rate) about body fixed coordinate (z) axis |
| X_ , Y_ | Force component along body fixed coordinate axis |
| N_ | Moment component about body fixed coordinate (z) axis |
| $\Psi$ | Yaw angle |
| m | Mass of AUV II |
| $I_{zz}$ | Moment of inertia about the body fixed coordinate (z) axis |
| F_ | External force applied to the vehicle |
| M_ | External moment applied to the vehicle |

**Subscripts**

| | |
|---|---|
| f | External force or moment component due to net hydrodynamic loads on the vehicle |
| uu , vv , rr | Hydrodynamic force or moment component due to square law drag |
| $\dot{u}, \dot{v}, \dot{r}$ | Hydrodynamic force or moment component due to added mass |
| Prop | Stern propulsion motor |
| Thrust | Thruster |

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that $x_G$ is positive), while $x_G$ and $y_G$ are zero. Additionally, it was assumed that the inertial properties of the AUV are symmetric. Therefore, the motions of interest involve only the variables u, v and r (surge, sway and angular yaw velocities).

The equations of motion for the AUV were then written as follows:

$$m\dot{u} = mvr + X_f$$

$$m\dot{v} = -mur + Y_f$$

$$I_{zz}\dot{r} = N_f$$

$$\dot{\Psi} = r$$

$$\dot{X} = u\cos\Psi - v\sin\Psi$$

$$\dot{Y} = u\sin\Psi + v\cos\Psi$$

In the above equations, $X_f$, $Y_f$ and $N_f$ are changes in hydrodynamic forces on the vehicle body resulting from propulsor action and vehicle motion. They arise from hydrodynamic lift, drag and added mass origins. It was further assumed that for hover conditions, lift forces arising from small angles of drift, were minimal. The forces acting on the vehicle were then limited to added mass effects, drag and the maneuvering forces generated by the thrusters and stern propulsion motors.

The drag forces were modeled as being proportional to the square of the velocity using the absolute value to account for direction. Using dimensional hydrodynamic coefficients, the external force and moment equations were assumed to be simplified to the following expressions:

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$$X_f = X_{\dot{u}}\dot{u} + X_{uu}u|u| + F_{Prop}$$

$$Y_f = Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} + Y_{vv}v|v| + Y_{rr}r|r| + F_{Thrust}$$

$$N_f = N_{\dot{r}}\dot{r} + N_{\dot{v}}\dot{v} + N_{rr}r|r| + N_{vv}v|v| + M_{Thrust}$$

Substituting these expressions in to the equations of motion resulted in the following:

$$m\dot{u} = mvr + X_{\dot{u}}\dot{u} + X_{uu}u|u| + F_{Prop}$$

$$m\dot{v} = -mur + Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} + Y_{vv}v|v| + Y_{rr}r|r| + F_{Thrust}$$

$$I_{zz}\dot{r} = N_{\dot{r}}\dot{r} + N_{\dot{v}}\dot{v} + N_{rr}r|r| + N_{vv}v|v| + M_{Thrust}$$

$$\dot{\Psi} = r$$

$$\dot{X} = u\cos\Psi - v\sin\Psi$$

$$\dot{Y} = u\sin\Psi + v\cos\Psi$$

Unlike standard maneuvering equations of motion, the square law drag terms do not nondimensionalize into a set of constant coefficient ordinary differential equations with definable stability limits independent of nominal forward speed.

## 2. Estimation of the Hydrodynamic Coefficients

Relatively accurate values for certain hydrodynamic coefficients $(X_{\dot{u}}, X_{uu}, Y_{\dot{v}}, Y_{\dot{r}}, N_{\dot{v}}$ and $N_{\dot{r}})$ in the equations of motion have been developed and experimentally verified by Warner (1991), however these hydrodynamic coefficients were determined at much higher vehicle velocities than that which would occur during hover positioning. Additionally, no previous estimates were available for the remaining hydrodynamic coefficients for the square law drag $(Y_{vv}, Y_{rr}, N_{vv}$ and $N_{rr})$.

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To determine estimates of the hydrodynamic coefficients, comparisons between the theoretical model and the experimental data were made.

A computer program using Euler integration methods was written using the equations of motion to simulate the motion of the AUV in the horizontal plane. The code for the MATLAB (trademark of Math Works, Inc.) program is provided in Appendix G. As a starting point, the hydrodynamic coefficients determined by Warner (1991) were used. In addition, the hydrodynamic coefficients for the linear drag were used as first estimates for the square law drag hydrodynamic coefficients.

The program was run for each of the three positioning experiments, comparing the results for one particular test, from each experiment. The coefficients were adjusted so as to achieve the best agreement between the model and the experimental data, with the hydrodynamic coefficients common for all three types of positioning experiments. The hydrodynamic coefficients were adjusted to one significant digit. Table 4.2 lists the initial and final values for the hydrodynamic coefficients.

A large difference was noted between the initial and final values for $X_{uu}$. The initial value was derived for the case where the vehicle was moving at a nominal steady state, average speed of 1.5 feet per second (Warner, 1991). Under these conditions, the stern propulsion motors are operating with a thrust reduction effect due to the forward motion of the vehicle. This thrust reduction can be modeled, similarly to drag, by a square law force as follows:

**TABLE 4.2** AUV II HYDRODYNAMIC COEFFICIENTS:
HOVER CONDITIONS

| HYDROYNAMIC COEFFICIENTS | INITIAL VALUE | FINAL VALUE |
|---|---|---|
| Xuu | -0.4024 | -3.0 |
| Xudct | -0.00282*377.67 | -0.06*377.67 |
| Yvv | -0.10700*51.72 | -0.5*51.72 |
| Yrr | 0.01187*377.67 | 0.01187*377.67 |
| Yvdot | -0.03430*377.67 | -0.04*377.67 |
| Yrdot | -0.00178*2756.81 | -0.00178*2756.81 |
| Nvv | -0.00769*377.67 | -0.00769*377.67 |
| Nrr | -0.00390*2756.81 | -0.04*2756.81 |
| Nvdot | -0.00178*2756.81 | -0.001*2756.81 |
| Nrdot | -0.00047*20137.50 | -0.002*20137.50 |

$$F_{Prop} = F_o + X_{Reduct}u|u|$$

where $F_o$ is the nominal static force of the stern propulsion motor equal to five pounds (Saunders, 1990).

The final value of $X_{uu}$ from Table 4.2 can be considered to be representative of the combined effects of drag and thrust reduction such that (to one decimal place):

$$X_{uu\ (Final)} \approx X_{uu\ (Drag)} + X_{uu\ (Reduct)}$$

$$X_{uu\ (Drag)} = -0.4$$

$$X_{uu\ (Reduct)} = -2.6$$

These results predict a steady state speed for the vehicle, at maximum voltage, of 1.3 feet per second.

### 3. Theoretical Model Results

Comparison between the experimental data and that predicted by the theoretical model, for the yaw positioning experiment is shown in Figure 4.17. The results for a 90 degree test are shown. The yaw position curve shows that less overshoot is predicted by the model than that measured experimentally, however the vehicle approached the final commanded position with less oscillation. Similar dynamic characteristics are seen in the yaw rate and thruster voltage curves.

The results for the lateral positioning experiment are shown in Figure 4.18. A comparison of Test 3 (see Table 3.2) is shown. The lateral position curve shows similar dynamic characteristics between the model and the

78
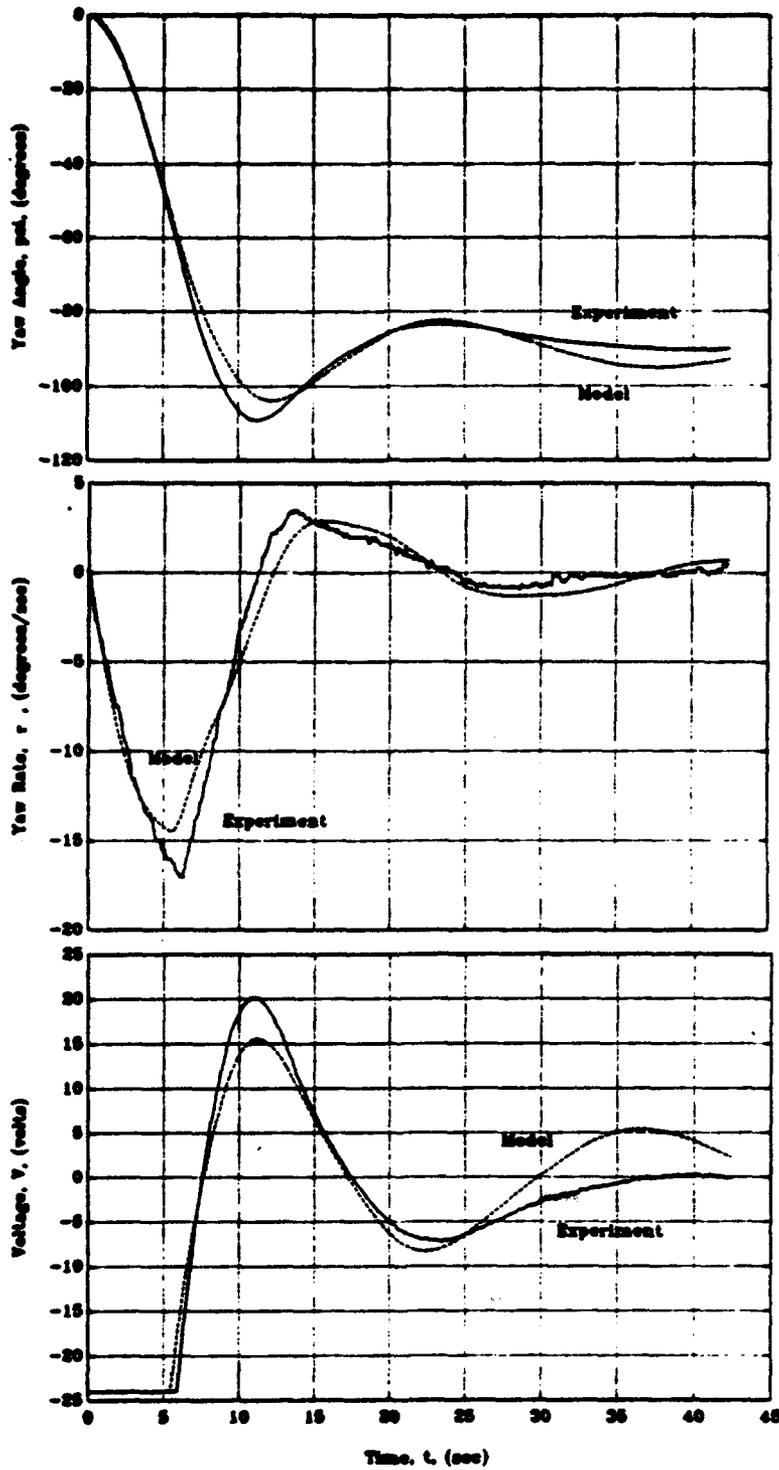
**Figure 4.17** AUV Model: Yaw Position Experiment

79
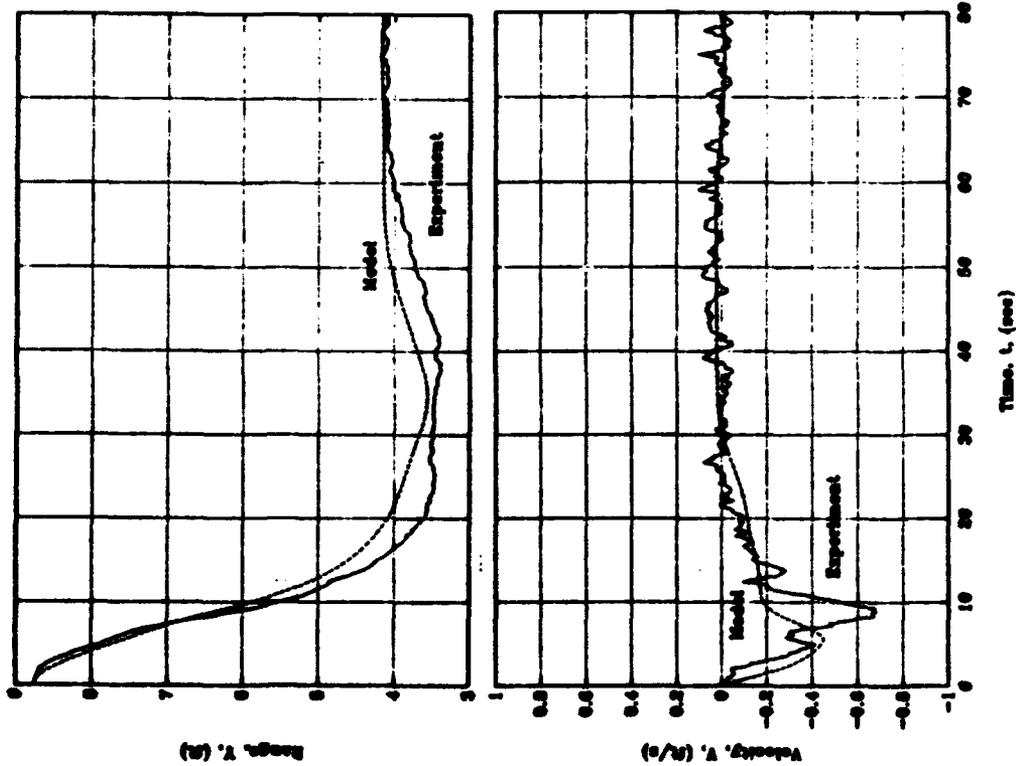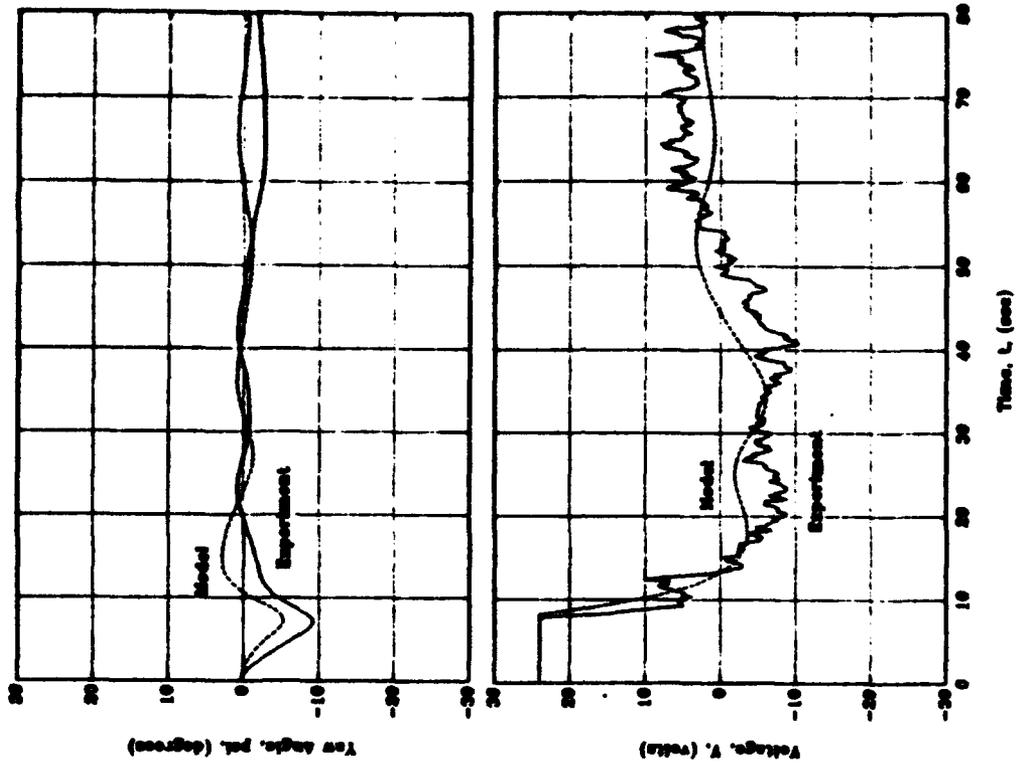
Figure 4.18   AUV Model: Lateral Position Experiment (Test 3)

experimental data, however the model reached a peak velocity, of smaller magnitude, sooner than the vehicle.

Similar dynamic characteristics are shown in the yaw position curve for the lateral positioning experiment as were observed for the yaw positioning experiment. The model shows less overshoot and a more oscillatory approach to the final commanded position than the data. The difference in the steady state positions, due to the stiction in the vehicle's thrusters is also shown. Similar features are shown in the thruster voltage curve.

Figure 4.19 shows the results for the longitudinal positioning experiment comparison. The comparison was made for Test 7 (see Table 3.2). Very good agreement is shown between the model and the data for the longitudinal range and surge velocity curves. The model shows the same overshoot as the data with only a slightly oscillatory approach to the final commanded position. A slight difference in peak value and time of occurrence is shown in the velocity curve. The same characteristics are shown in the stern propulsion voltage curve.

The stiction in the thrusters and stern propulsion motors is shown in the difference between the yaw position curves for the model and the data.
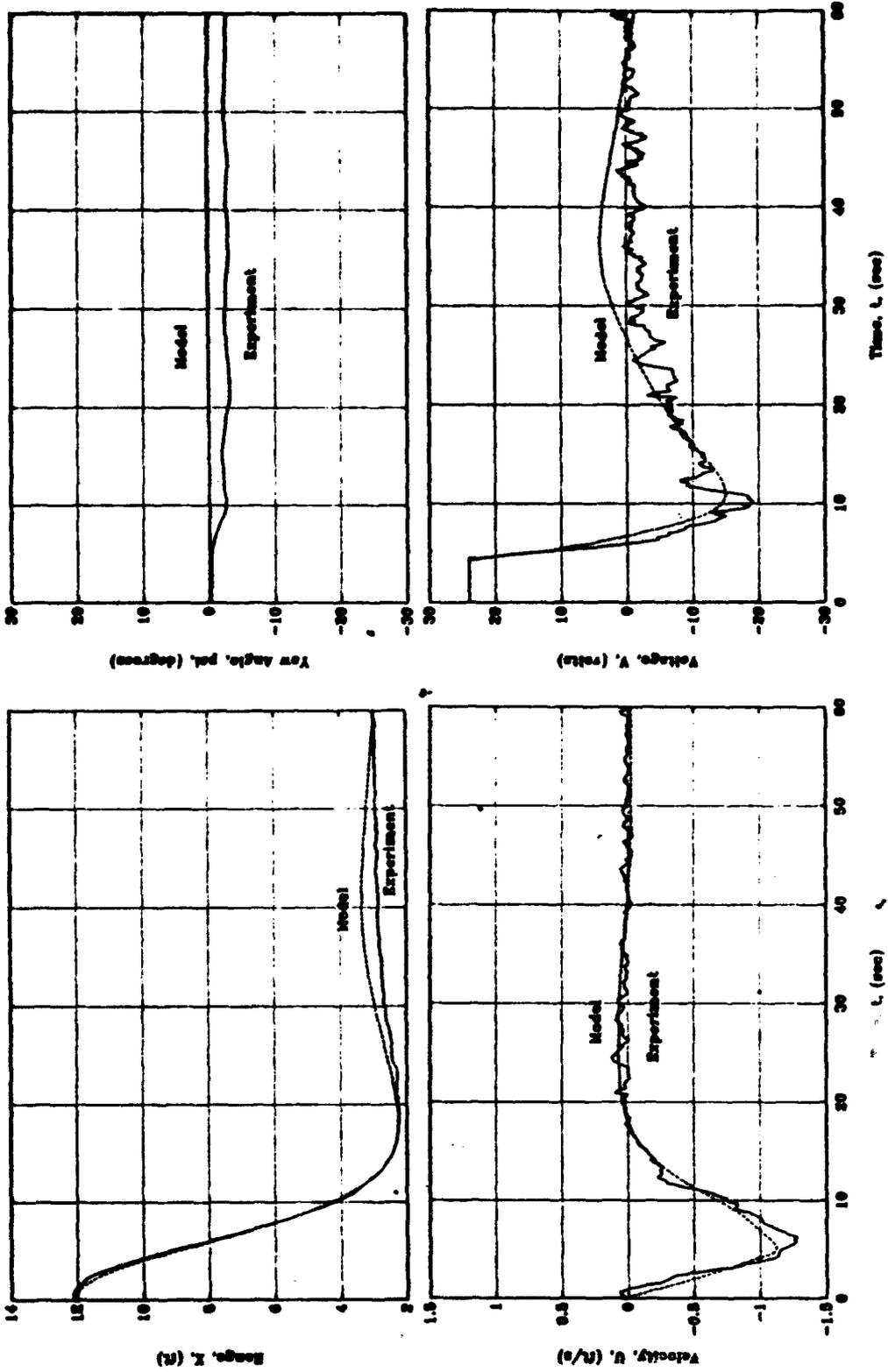
**Figure 4.19** AUV Model: Longitudinal Position Experiment (Test 7)

# V. SUMMARY

This chapter documents generalized conclusions of the results presented in Chapter IV. Specific comments regarding the level of success in meeting the objectives of this study are included. Recommendations for areas of further study, related to the concepts discussed in this thesis are made.

## A. CONCLUSIONS

Through the course of this study, the ability to achieve accurate acoustic positioning capabilities of the NPS Autonomous Underwater Vehicle (AUV II) under hover conditions was demonstrated.

Use of an independent self-sonar which provided environmental imaging data without the aid of a transponder, along with the inputs from a free directional gyro system provided adequate data from which to base vehicle positioning commands.

Execution of the maneuvering commands through the use of stern propulsion motors and lateral tunnel thrusters, proved vital in achieving the ability to accurately position the vehicle, based on sensor data inputs.

The results of the yaw positioning experiment showed that an accurate final commanded angular position can be achieved using the yaw position inputs from the free directional gyro system and maneuvering commands executed by the thrusters.

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Accurate lateral and longitudinal positioning, in the vicinity of a local target, was achieved through the combined input data from the gyro and the sonar systems, and the combined maneuvering efforts of the stern propulsion motors and the thrusters. The stability of the positioning data relative to the target, however was dependent on the gain of the sonar. Overdriving the sonar transducer resulted in unstable positioning data. This indicates that in future missions, an automatic "sonar supervisor" must be included in the control software.

The proportional derivative control law employed to generate the maneuvering commands produced the expected vehicle motion dynamics. The ability to change the dynamic motion characteristics (overshoot and oscillation), was achieved by adjusting the control law gains.

In the cases where the control effort was governed by a combination of position errors (yaw position and range) as seen in the lateral and longitudinal positioning experiments, the stability of the positioning ability was dependent on the coupling effects of the two directions of motion. The motion became particularly unstable in the situations where the position errors resulted in saturation of the thrusters.

Motor stiction affected the error in the final commanded positions, in all of the positioning experiments. The level of stiction in the thrusters limited the ability to achieve the final commanded yaw position and lateral range in both the yaw and lateral positioning experiments. The experimental results showed that the level of stiction was not identical for both thrusters, nor was it the same for either direction for one thruster.

The motor stiction effects were worsened in the case of the longitudinal positioning experiment where the stern propulsion motors generated a yaw moment on the vehicle, which was below the threshold of the lateral thruster response.

The results of the theoretical model provided adequate data to support a model based control effort, however, several effects which were beyond the scope of this study, were not included. Some of which include the following:

1. Motor stiction, as previously discussed.

2. Changes in thruster and stern propulsion force effects due to changes in the velocity of the vehicle.

3. Changes in effects of the hydrodynamic coefficients due to changes in vehicle velocity.

## B.  RECOMMENDATIONS FOR FURTHER STUDY

This thesis examined the first experiments conducted to study the ability of the NPS AUV II to achieve acoustic dynamic positioning during hover conditions. As a result, several related areas require further research.

Proportional derivative control laws were used to generate the positioning commands for the AUV with favorable results, however optimization of the control law gains is still required. In addition, other types of control methods which may be incorporated, should be studied. In particular, sliding mode control, using model based command generators, should be examined for its suitability to support dynamic positioning behaviors without driving thrusters into saturated conditions.

Further work is required in the area of modeling the motion of the AUV during hover conditions. Certain areas of concern, such as thruster and stern propulsion motor thrust effectiveness and hydrodynamic forces require further research if generalizations of the model were to be pursued.

Experiments should be conducted, to verify higher levels of autonomous operation by examining more complex motion behaviors, including longer missions, combining motions commanded in sequence or simultaneously, using either timed based or sensory data based inputs as the basis for the selection of behaviors.

Using sonar to identify objects of interest within the field of view should be integrated into the capabilities of the robot submarine, although delays in the availability of position related information are likely to cause positional motion instability. A study and development of model based predictor/corrector control is likely to be a requirement for maintaining stable combined motion.

Investigations of disturbance response in the presence of water current could and should be conducted.

# APPENDIX A   AUV II CONFIGURATION BLOCK DIAGRAM

A simplified block diagram of the major equipment groups is provided on the following page. This diagram shows the basic system power paths and the computer data transfer paths between the components.

SCAN SONAR
Tritech
ST-725

PROFILE SONAR
Tritech
ST-1000

RATE GYROS
Humphrey
RG02-2324-1
Roll Pitch
Yaw

VERTICAL GYRO
Humphrey
VG34-0361-2
Roll    Pitch

+24V

24 Volt
Screw
Thruster
Gyro
Battery
Pack
2 ea
LCL12V38P

+24V

-24V

+24V

-24V

F

E

CRYDOM
6300 TTL
s.s.relays
3 each

+5 Volt

+24V

D

C

+15V

+/-15V
Reference
Source

SONARS (2)
Datasonics
PSA 900

24 Volt
Computer
Analog
Battery
Pack
2 ea
LC112P38P

+24V

B

A

+15 Dc-DC
Calex 12S15.
1000 ma

-15 DC-DC
Calex 46S
700 ma

DIAGNOSTIC VOLTAGE
SOURCES

CONTROL
COMPUTER
Invertor
ACON RUMT2405-
12TS
+5 +/-12

MISSION
COMPUTER
Invertor
ACON RUMT2405-
12TS
+5 +/-12

Servo
Amp
AMC
30A8

Servo
Amp
AMC
30A8

Servo
Amp
AMC
30A8

Servo
Amp
AMC
30A8

SCREW MOTORS

THR

+24V

TACHOMETER SOURCES SCRE
RPA PADDLE WHEEL

+5 Volt

LINE LEGEND

Power

Computer in

Computer out

Control
Surface
Servo

Control
Surface
Servo

Control
Surface
Servo

Control
Surface
Servo

Control
Surface
Servo

A

AUV SIMPLIFIED
BLOCK DIAGRAM
TomC 01/26/94

# APPENDIX B   AUV II WIRING LIST

The wiring list for the current configuration of the AUV II is presented on the following pages.

For each item shown, the type of signal carried or channel is listed along with the terminal pin assignment, color, voltage rating and description.

Further wiring details can be found in the manufacturer's technical manual for the individual component.

| ITEM | SIG NAME/CONN | TERM | COLOR | TYPE | TO/FROM |
|------|---------------|------|-------|------|---------|
| BATT FWD, COMPUTER/ANALOG PS | | POS | WHT | POW 24VDC | CIRC BRKER, PT. Ao |
| | | NEG | BLK | GND | GND/REF BUSS |
| BATT, AFT, GYROS/PROPS AND THRUSTERS | | POS | WHT | POW 24VDC | CIRC BRKER, PT. Co |
| | | NEG | BLK | GND | GND/REF BUSS |
| RELAY, MAIN POWER | | PT A, HOT | WHT | POW 24VDC | COMP/AN CIRC BRKR |
| | | | RED | POW 24VDC | TERM A, POWR THRUHULL |
| | | | RED | POW 24VDC | FUSE BLOCK 1, (TH A1) |
| | | PT B | WHT | POW 24VDC | FUSE BLK 1, ANAL/COMP |
| | | PT C, HOT | WHT | POW 24VDC | GYRO/SCREW CIRC BRKR |
| | | | RED | POW 24VDC | TERM C, POWR THRUHULL |
| | | PT D | WHT | POW 24VDC | FUSE BLK 3, SERVO AMP |
| | | ACTUAT + | ORG | CNTL 24VDC | TERM B1, POW THRUHULL |
| | | ACTUAT - | ORG/GRN | GND | GND/REF BUSS |
| CIRC BRKR, ANALOG P.S. AND COMPUTERS | | PT Ao | WHT | POW 24VDC | ANAL/COMP BATT |
| | | 30 AMP | WHT | POW 24VDC | TERM A, MASTER RELAY |
| CIRC BRKR, SERVO AMPS | | PT Co | WHT | POW 24VDC | GYRO/SCREW BATT |
| | | PT Co | WHT | POW 24VDC | GYRO CIRC BRKER |
| | | 30 AMP | WHT | POW 24VDC | TERM C, MASTER RELAY |
| CIRC BRKR, GYROS | | HOT | WHT | POW 24VDC | PT Co ( on SERVO CIR BRKR) |
| | | 8 AMP | WHT | POW 24VDC | FUSE BLK 2, GYROS |
| ANALOG POW SUPPLY BOARD | ANALOG DIG GND | AN/DIG GND | BLK | GND/REF | CELESCO DEPTH CELL BOARD T15 |
| | A/D GND | A/D GND, P3 | BLK | GND/REF | DATASONICS SONAR BOARD T2 |
| | A/D GND | A/D GND, P3 | GREY | GND/REF | ICU-2A BRKOUT (ADC-1 SL5) T P2 |
| | A/D GND | A/D GND, P3 | GREY | GND/REF | ICU-2A BRKOUT (ADC-2 SL 6) T P2 |
| | A/D GND | A/D GND, P3 | BLK | GND/REF | SERVO FIN CONNECTION |
| | A/D GND | A/D GND, P2 | BLK | GND/REF | ACOM P.S. (BOTH), COM CONN. |
| | A/D GND | A/D GND, P2 | BLK | GND/REF | -24 VDC GND BUSS |
| | 15 POW CNTRL | P2-1 | WHT | TTL CNTRL | PIA-3A BRKOUT T35 |
| | 5 POW CNTRL | P1-3 | WHT/BRN | TTL CNTRL | PIA-3A BRKOUT T37 |
| | POW SUPPLY | P1-2 | WHT | 24 VDC | MASTER RELAY  TERM B |
| | POW RETURN | P1-1 | BLK | POW RTN | ANALOG -24 VDC GND BUSS |
| | +5 POW | P4 | RED | +5 VDC POW | FIN SERVO CONNECTOR |
| | +5 | P4 | RED | DIAGNOSTICS | ICU-2A BRKOUT (ADC-1), T2 |
| | +5 | P4 | no conn | | |
| | +15 POW | P5 | RED/WHT | +15 VDC POW | DATASONICS SONAR BOARD T3 |
| | +15 | P5 | RED | +15 VDC POW | CELESCO DEPTH CELL, T13 |
| | +15 | P5 | RED/WHT | DIAG | ICU-2A BRKOUT (ADC-1), T0 |
| | -15 POW | P6 | BLK | -15 VDC POW | CELESCO DEPTH CELL T12 |
| | -15 | P6 | no conn | | |
| | -15 | P6 | RED/BLK | DIAG | ICU-2A BRKOUT (ADC-1), T1 |
| | +10 POW | P7 | ORG/RED | +10 VDC REF | RATE GYROS TERM F |
| | +10 | P7 | ORG/RED | +10 VDC REF | VERT GYROS TERM E & J |
| | +10 | P7 | ORG/RED | DIAG | ICU-2A BRKOUT (ADC-1), T3 |
| | -10 POW | P8 | ORG/BLK | -10 VDC REF | RATE GYROS TERM E |
| | -10 | P8 | ORG/BLK | -10 VDC REF | VERT GYROS TERM H & L |

| | | | | | |
|---|---|---|---|---|---|
| | -10 | P8 | ORG/BLK | BIAS | ICU-2A BRKOUT (ABC-1), T4 |
| FB CAGE | RELAYED POW | P9-3 | BLK | -24 VDC RTN | FB DB25 T12 |
| FB UNCAGE | RELAYED POW | P9-2 | WHT | -24 VDC RTN | FB DB25 T11 |
| TRITECH SONAR | RELAYED POW | P9-1 | WHT | 24 VDC | TRITECH CONN PIN 3 |
| FB CAGE RELAY | RELAY CNTRL TTL | P10-3 | GRN/WHT | TTL CNTRL | PIA-3A BRKOUT T50 |
| FB UNCAGE RELAY | RELAY CNTRL TTL | P10-2 | GRN/BLK | TTL CNTRL | PIA-3A BRKOUT T48 |
| TRITECH SONAR RELAY | RELAY CNTRL TTL | P10-1 | GRN | TTL CNTRL | PIA-3A BRKOUT T46 |

**TRANSPORT PLUG TO SPIN**
**GYROS, CONN TO THRUHULL**
**INSIDE/OUTSIDE**

| | | | | | |
|---|---|---|---|---|---|
| ORG | B1 | RED | | | |
| RED | A1 | ORG | | | |
| WHT | C | WHT | | | |
| BLK | A | WHT/BLK | | | |
| GRN, BAT GND BUS | E | BLU | GND | SPIN GYROS | |
| WHT/BLK, GYROS | F | BLK | POW, 24V | JUMPED TO E | |

**RUN PLUG FOR NORMAL OPERATION**

| | | | | | |
|---|---|---|---|---|---|
| MASTER RELAY SOLENOID | ORG | B1 | RED | CNTL 24VDC | CLOSE MASTER RELAY |
| 24VDC POW | RED | A1 | ORG | POW 24VDC | JUMPED TO B1 |
| INSIDE/OUTSIDE | WHT | C | WHT | | |
| | BLK | A | WHT/BLK | | |
| | GRN, BAT GND BUS | E | BLU | GND | SPIN GYROS |
| | WHT/BLK, GYROS | F | BLK | POW, 24V | JUMPED TO E |

**THRUHULL, POWER, AUV**
**INSIDE PIGTAIL TO**
**INSIDE CONNECTIONS**

| | | | | | |
|---|---|---|---|---|---|
| ORG | B1 | ORG | CNTL 24VDC | PT B1, MASTER RELAY | |
| RED | A1 | RED | POW 24VDC | FUSE BLOCK 1, 1 AMP | |
| WHT | C | RED | CHG GYRO BA | TERM C, MASTER RELAY | |
| BLK | A | RED | CHG COMP BA | TERM A, MASTER RELAY | |
| GRN | E | BLK | GND | GND/REF BUSS | |
| WHT/BLK | F | BLK | POW RTN | GYRO FUSE BLK 2 | |

**UMBILICAL/BENCH BOX**
**THRU-HULL OUTSIDE**
**PIGTAIL TO UMBILICAL**

| | | | | | |
|---|---|---|---|---|---|
| RED | B1 | RED | CNTL 24VDC | TOGGLE SW., CONN A1 | |
| ORG | A1 | ORG | POW 24VDC | 1 AMP FUSE/SWITCH | |
| WHT | C | WHT | CHARGE BATT | 5 AMP FUSE, RED RECPT | |
| WHT/BLK | A | GRN | CHARGE BATT | 5 AMP FUSE, RED RECPT | |
| BLU | E | BLU | GND | BLK BANANA RECEPT.(2) | |
| BLK | F | BLK | POW RET | SW. TOGGLE, CONN E | |

**FUSE BLOCK 1, FWD**

| | | | |
|---|---|---|---|
| IN | WHT | POW 24VDC | TERM B, MASTER RELAY |
| 5 AMP | WHT | POW 24VDC | ANALOG P.S. |
| 0.1 AMP | WHT | POW 24VDC | TURBO PROBE |
| 10 AMP | WHT | POW 24VDC | ACON P.S.(2) OS9, DOS |
| IN | RED | POW 24VDC | PT A, MASTER RELAY |
| 1 AMP | RED | POW 24VDC | PT A1, POWER THRUHULL |

**FS BLOCK 2, AFT, GYRO**

| | | | |
|---|---|---|---|
| IN | WHT | POW 24VDC | GYRO CIRC BRKR |
| 5 AMP | RED | POW 24VDC | RATE GYROS (3) |
| 2 AMP | RED | POW 24VDC | VERTICAL GYROS (2) |
| 2 AMP | RED | POW 24VDC | FREE GYRO POW INVERT. |
| RET | BLK | POW RTN | RATE GYROS (3) |
| RET | BLK | POW RTN | VERT GYROS (2) |
| RET | BLK | POW RTN | FREE GYRO POW INVERT. |
| RET | BLK | POW RTN | TERM F, POW THRUHULL |

| | | | | | |
|---|---|---|---|---|---|
| FS BLOCK 3, SERVO AMP | | POW SUPPLY | WHT | POW 24VDC | TERM 9, MASTER RELAY |
| | THR | 5 AMPS | WHT | POW 24VDC | FOR/VERT THR SERVO T4 |
| | THR | 5 AMPS | WHT | POW 24VDC | FOR/HOR THR SERVO T4 |
| | THR | 5 AMPS | WHT | POW 24VDC | AFT/VERT THR SERVO T4 |
| | THR | 5 AMPS | WHT | POW 24VDC | AFT/HOR THR SERVO T4 |
| | PROP | 10 AMPS | WHT | POW 24VDC | STBD MAIN SERVO T4 |
| | PROP | 10 AMPS | WHT | POW 24VDC | PORT MAIN SERVO T4 |
| FREE GYRO (UN)CAGE | | 5 AMPS | RED | POW 24VDC | FREE GYRO TERM 14 |
| | | | | | |
| GND/REF BUSS | | BUSS | BLK | GND/REF | ANALOG P.S. ANAL GND |
| | | BUSS | BLK | POW RTN | TRITEK PROF. SONAR |
| | | BUSS | BLK | POW RTN | TRITEK SCAN SONAR |
| | | BUSS | BLK | POW RTN | ACON P.S.(COMPUTERS) |
| | | BUSS | BLK | GND | COMP./ANALOG BATT.,- |
| | | BUSS | BLK | GND | GYRO/MOTOR BATT.,- |
| | | BUSS | BLK | POW RTN | TERM E, POW THRUHULL |
| | | BUSS | ORG/GRN | POW RTN | ACTUAT-, MASTER RELAY |
| | | BUSS | BLK | POW RTN | ANALOG P.S.,24V RET |
| | | BUSS | BLK | POW RTN | SERVO AMPS, FUSE BLK3 |
| | | | | | |
| OS9 ACON P.S. INVERTER | GND | 3 | BLK | POW RTN | GND/REF BUSS |
| | POW | 5 | WHT | POW 24VDC | FUSE BLK 1 |
| | SENS | 8 | BLK | SENS | JUMPED TO 9 & 13 |
| | | | BLK | GND/REF | POW RTN RPM SENSORS |
| | GND | 9 | BLK-WHT | GND/REF | OS9 COMPUTER GND |
| | | | BLK | GND/REF | JUMPED TO 8 & 13 |
| | GND | 13 | BLK | COMM/REF | ANAL P.S., ANAL GND |
| | | | BLK | GND/REF | JUMPED TO 8 & 9 |
| | POW | 10 | WHT | POW +5VDC | OS9 COMPUTER |
| | | | WHT | POW | JUMPED TO 11 |
| | POW | 11 | RED | POW +5VDC | RPM SENSORS |
| | | | WHT | SENS | JUMPED TO 10 |
| | POW | 12 | WHT | POW -12VDC | OS9 -12VDC SUPPLY |
| | POW | 14 | WHT | POW +12VDC | OS9 +12VDC SUPPLY |
| | | | | | |
| OS9 COMPUTER | | GND | BLK-WHT | GND/REF | TERM 9, OS9 ACON P.S. |
| | | +5VDC | WHT | POW +5VDC | TERM 10, OS9 ACON |
| | | +12VDC | WHT | POW +12VDC | TERM 14, OS9 ACON |
| | | -12VDC | WHT | POW -12VDC | TERM 12, OS9 ACON |
| OS9 COMPUTER BOARDS | | RIBBON | GRY | CNTRL, I/O | BREAK OUT BOARDS (4) |
| | | | | | |
| DOS ACON P.S. INVERTER | | 3 | BLK | POW RTN | GND/REF BUSS |
| | | 5 | WHT | | |
| | | 8 | BLK | SENS | JUMPED TO 9 & 13 |
| | | 9 | BLK | GND/REF | JUMPED TO 8 & 13 |
| | | 13 | BLK | GND/REF | JUMPED TO 8 & 9 |
| | | 10 | WHT | POW | JUMPED TO 11 |
| | | 11 | WHT | SENS | JUMPED TO 10 |
| | | 12 | | | |
| | | 13 | | | |
| | | 14 | | | |
| | | | | | |
| DOS COMPUTER | | | | | |
| | | | | | |
| SERVO AMP PORT MAIN SCREW | | 1 -N | BLK | POW RTN | PORT MAIN MOTOR, BLK |
| | | 2 +N | WHT | VAR POW | PORT MAIN MOTOR, RED |

|  |  |  |  |  |
|---|---|---|---|---|
|  | 3 POW GND | BLK | POW RTN | FUSE BLOCK 3 |
|  | 4 HI VOLT | WHT | POW 24VDC | FUSE BLOCK 3 |
|  | CONN 2 | GREY | SIG GND | JUMPED TO PIN 5 |
|  | CONN 4 | RED | + REF IN | DAC-2B BKOUT SL11 T30 |
|  | CONN 5 | GREY | - REF | DAC-2B BKOUT SL11 T27 |
|  | CONN 8 | VIOL | CURR MON | ICU-2A, SL 6, T 00 |
|  | CONN 11 | BLU | INHIB | PIA-3A, SL 4, T 26 |
| SERVO AMP STBD MAIN SCREW | 1 -M | BLK | POW RTN | STBD MAIN MOTOR, BLK |
|  | 2 +M | WHT | VAR POW | STBD MAIN MOTOR, RED |
|  | 3 POW GND | BLK | POW RTN | FUSE BLOCK 3 |
|  | 4 HI VOLT | WHT | POW 24VDC | FUSE BLOCK 3 |
|  | CONN 2 | GREY | SIG GND | JUMPED TO PIN 5 |
|  | CONN 4 | ORANG | + REF IN | DAC-2B BKOUT SL11 T32 |
|  | CONN 5 | GREY | - REF | DAC-2B BKOUT SL11 T29 |
|  | CONN 8 | BLU | CURR MON | ICU-2A, SL 6, T 1 |
|  | CONN 11 | VIOL | INHIBIT | PIA-3A, SL 4, T 24 |
| SERVO FOR/VERT THRUSTER | 1 -M | BLK | POW RTN | FOR/VERT THRUSTER,BLK |
|  | 2 +M | WHT | VAR POW | FOR/VERT THRUSTER,RED |
|  | 3 POW GND | BLK | POW RTN | FUSE BLOCK 3 |
|  | 4 HI VOLT | WHT | POW 24VDC | FUSE BLOCK 3 |
|  | CONN 2 | GREY | SIG GND | JUMPED TO PIN 5 |
|  | CONN 4 | BLU | + REF IN | DAC-2B BKOUT SL11 T34 |
|  | CONN 5 | GREY | - REF | DAC-2B BKOUT SL11 T31 |
|  | CONN 8 | YEL | CURR MON | ICU-2A, SL 6, T 3 |
|  | CONN 11 | BRN | INHIBIT | PIA-3A, SL 4, T 22 |
| SERVO FOR/HOR THRUSTER | 1 -M | BLK | POW RTN | FOR/HOR THRUSTER, BLK |
|  | 2 +M | WHT | VAR POW | FOR/HOR THRUSTER, RED |
|  | 3 POW GND | BLK | POW RTN | FUSE BLOCK 3 |
|  | 4 HI VOLT | WHT | POW 24VDC | FUSE BLOCK 3 |
|  | CONN 2 | GREY | SIG GND | JUMPED TO PIN 5 |
|  | CONN 4 | BLK | +REF IN | DAC-2B BKOUT SL11 T36 |
|  | CONN 5 | GREY | -REF | DAC-2B BKOUT SL11 T33 |
|  | CONN 8 | WHT | CURR MON | ICU-2A, SL 6, T 4 |
|  | CONN 11 | YEL | INHIBIT | PIA-3A, SL 4, T 20 |
| SERVO AFT/VERT THRUSTER | 1 -M | BLK | POW RTN | AFT/VERT THRUSTER,BLK |
|  | 2 +M | WHT | VAR POW | AFT/VERT THRUSTER,RED |
|  | 3 POW GND | BLK | POW RTN | FUSE BLOCK 3 |
|  | 4 HI VOLT | WHT | POW 24VDC | FUSE BLOCK 3 |
|  | CONN 2 | GREY | SIG GND | JUMPED TO PIN 5 |
|  | CONN 4 | YEL | +REF IN | DAC-2B BKOUT SL11 T38 |
|  | CONN 5 | GREY | -REF | DAC-2B BKOUT SL11 T35 |
|  | CONN 8 | BLU | CURR MON | ICU-2A, SL 6, T 5 |
|  | CONN 11 | GRN | INHIBIT | PIA-3A, SL 4, T 18 |
| SERVO AFT/HOR THRUSTER | 1 -M | BLK | POW RTN | AFT/HOR THRUSTER, BLK |
|  | 2 +M | WHT | VAR POW | AFT/HOR THRUSTER, RED |
|  | 3 POW GND | BLK | POW RTN | FUSE BLOCK 3 |
|  | 4 HI VOLT | WHT | POW 24VDC | FUSE BLOCK 3 |
|  | CONN 2 | GREY | SIG GND | JUMPED TO PIN 5 |
|  | CONN 4 | WHT | +REF IN | DAC-2B BKOUT SL11 T40 |
|  | CONN 5 | GREY | -REF | DAC-2B BKOUT SL11 T37 |
|  | CONN 8 | ORG | CURR MON | ICU-2A, SL 6, T 6 |
|  | CONN 11 | ORG | INHIBIT | PIA-3A, SL 4, T 16 |
| PROP, STB MAIN SCREW | RED | WHT | VAR POW | STB MAIN SERVO, +M |
|  | BLK | BLK | POW RTN | STB MAIN SERVO, -M |
|  | RPM GND | BLK | GND/REF | OS9 ACOM P.S., T 8 |
|  | RPM 3 CHA | ORG | TACH | TIM-1A, SL 7, T 3 |

| | | | | |
|---|---|---|---|---|
| | RPM 4 Vcc | RED | POW 5VDC | 069 ACOM P.S., T 11 |
| PROP, PORT MAIN SCREW | RED | WHT | VAR POW | PORT MAIN SERVO, +N |
| | BLK | BLK | POW RTN | PORT MAIN SERVO, -N |
| | RPM GND | BLK | GND/REF | 069 ACOM P.S., T 8 |
| | RPM 3 CHA | YEL | TACH | TIM-1A, SL 7, T 6 |
| | RPM 4 Vcc | RED | POW 5DC | 069 ACOM P.S., T 11 |
| THRUSTER, FOR/VERT | RED | WHT | VAR POW | FOR/VERT SERVO, +N |
| | BLK | BLK | POW RTN | FOR/VERT SERVO, -N |
| | RPM GND | BLK | GND/REF | 069 ACOM P.S., T 8 |
| | RPM 3 CHA | ORN/BLK | TACH | TIM-1A, SL 8, T 9 |
| | RPM 4 Vcc | RED | POW 5VDC | 069 ACOM P.S., T 11 |
| THRUSTER, FOR/HOR | SEE | FOR/VERT | | |
| | RPM 3 CHA | VIOL | TACH | TIM-1A, SL 8, T 10 |
| THRUSTER, AFT/VERT | SEE | FOR/VERT | | |
| | RPM 3 CHA | BLU/WHT | TACH | TIM-1A, SL 8, T 7 |
| THRUSTER, AFT/HOR | SEE | FOR/VERT | | |
| | RPM 3 CHA | WHT/BLK | TACH | TIM-1A, SL 8, T 8 |
| FIN SERVO CONN BOARD | SUPPLY | RED | POW 5 VDC | ANALOG P.S., 5 VDC |
| | OUT | RED | POW 5VDC | FIN SERVOS (8), T 3 |
| | OUT | RED | 5 VDC | FIN SIGNAL PULL-UP BOARD |
| | RET | BLK | GND | ANALOG P.S., GND/REF |
| | RET | BLK | GND | FIN SERVOS (8), T 2 |
| | REF | GREY | GND/REF | TIM BRKOUT, T23 and T24 |
| FIN SIGNAL BOARD | SUPPLY | RED | POW 5VDC | FIN SERVO 5 VDC POW CONN |
| inject 5VDC | OUT | WHT | 5 VDC | TIM BRKOUT, T11 |
| | | WHT | 5 VDC | TIM BRKOUT, T12 |
| | | WHT | 5 VDC | TIM BRKOUT, T13 |
| | | WHT | 5 VDC | TIM BRKOUT, T14 |
| | | WHT | 5 VDC | TIM BRKOUT, T17 |
| | | WHT | 5 VDC | TIM BRKOUT, T18 |
| | | WHT | 5 VDC | TIM BRKOUT, T19 |
| | | WHT | 5 VDC | TIM BRKOUT, T20 |
| FIN, FOR/TOP | 1 | BLK-VIOL | SIG | TIM-1A BRKOUT T11 |
| | 2 | BLK | GND/REF | FIN SERVO BOARD, GND |
| | 3 | RED | POW 5 VDC | FIN SERVO BOARD, POW |
| FIN, FOR/STBD | 1 | BLK-ORG | SIG | TIM-1A BRKOUT T14 |
| | 2 | BLK | GND/REF | FIN SERVO BOARD, GND |
| | 3 | RED | POW 5 VDC | FIN SERVO BOARD, POW |
| FIN, FOR/PORT | 1 | BLK-RED | SIG | TIM-1A BRKOUT T13 |
| | 2 | BLK | GND/REF | FIN SERVO BOARD, GND |
| | 3 | RED | POW 5 VDC | FIN SERVO BOARD, POW |
| FIN, FOR/BOT | 1 | BLK-YEL | SIG | TIM-1A BRKOUT T12 |
| | 2 | BLK | GND/REF | FIN SERVO BOARD, GND |
| | 3 | RED | POW 5 VDC | FIN SERVO BOARD, POW |
| FIN, AFT/TOP | 1 | BLK-WHT | SIG | TIM-1A BRKOUT T17 |

| | | | | | |
|---|---|---|---|---|---|
| | | 2 | BLK | GND/REF | FIN SERVO BOARD, GND |
| | | 3 | RED | POW 5 VDC | FIN SERVO BOARD, POW |
| FIN, AFT/STBD | | 1 | BLK-GRN | SIG | TIM-1A BRKOUT T20 |
| | | 2 | BLK | GND/REF | FIN SERVO BOARD, GND |
| | | 3 | RED | POW 5 VDC | FIN SERVO BOARD, POW |
| FIN, AFT/PORT | | 1 | BLK-ORG | SIG | TIM-1A BRKOUT T19 |
| | | 2 | BLK | GND/REF | FIN SERVO BOARD, GND |
| | | 3 | RED | POW 5 VDC | FIN SERVO BOARD, POW |
| FIN, AFT/BOT | | 1 | BLK-BRN | SIG | TIM-1A BRKOUT T18 |
| | | 2 | BLK | GND/REF | FIN SERVO BOARD, GND |
| | | 3 | RED | POW 5 VDC | FIN SERVO BOARD, POW |
| GYRO, PITCH RATE | P.S. REF | A | BLK | GND/REF | FUSE BLOCK 2, GND |
| | P.S. + DC | B | RED | 24 VDC | FUSE BLOCK 2, COMMON 5 AMP FUSE |
| | SIGNAL + | D | BRN | ANALOG SIG | ICU-2A BRKOUT (ADC-2), T8 |
| | SIG. -REF | E | GRN | -10 VDC REF | ANALOG P.S. BOARD, T P8 |
| | SIG +REF | F | WHT | +10 VDC REF | ANALOG P.S. BOARD, T P7 |
| GYRO, ROLL RATE | P.S. REF | A | BLK | GND/REF | FUSE BLOCK 2, GND |
| | P.S. + DC | B | RED | 24 VDC | FUSE BLOCK 2, COMMON 5 AMP FUSE |
| | SIGNAL + | D | BLK | ANALOG SIG | ICU-2A BRKOUT (ADC-2), T9 |
| | SIG. -REF | E | GRN | -10 VDC REF | ANALOG P.S. BOARD, T P8 |
| | SIG +REF | F | WHT | +10 VDC REF | ANALOG P.S. BOARD, T P7 |
| GYRO, YAW RATE | P.S. REF | A | BLK | GND/REF | FUSE BLOCK 2, GND |
| | P.S. + DC | B | RED | 24 VDC | FUSE BLOCK 2, COMMON 5 AMP FUSE |
| | SIGNAL + | D | WHT | ANALOG SIG | ICU-2A BRKOUT (ADC-2), T10 |
| | SIG. -REF | E | GRN | -10 VDC REF | ANALOG P.S. BOARD, T P8 |
| | SIG +REF | F | WHT | +10 VDC REF | ANALOG P.S. BOARD, T P7 |
| GYRO, VERTICAL PITCH & ROLL ANGLE | P.S. + DC | A | RED | 24 VDC | FUSE BLOCK 2, COMMON 2 AMP FUSE |
| | P.S. REF | B | BLK | GND/REF | FUSE BLOCK 2, GND |
| | ERECT CUTOUT | C | WHT | CNTRL | JUMPED TO D |
| | ERECT CUTOUT | D | GRN | CNTRL | JUMPED TO C |
| | SIG. + REF, ORG | E | ORG/RED | +10 VDC REF | ANALOG P.S. BOARD, T P7 |
| | SIG. + REF, YEL | J | ORG/RED | +10 VDC REF | SAME WIRE, T P7 |
| | SIG. - REF, BLU | H | ORG/BLK | -10 VDC REF | ANALOG P.S. BOARD, T P8 |
| | SIG. - REF, BLK | L | ORG/BLK | -10 VDC REF | SAME WIRE, T P8 |
| | PITCH ANGLE, SIG | F | BRN | ANALOG SIG | ICU-2A BRKOUT (ADC-2), T11 |
| | ROLL ANGLE, SIG | K | VIOL | ANALOG SIG | ICU-2A BRKOUT (ADC-2), T12 |
| GYRO, FREE, P.S. INVERTER | AC OUTPUT | 1A | RED | POW 115VAC | FG DB 25 CONN., T4 |
| | AC COMMON | 2B | WHT | AC GND/REF | FG DB 25 CONN., T7 |
| | AC OUTPUT | 3C | BLK | POW 26VAC | FG DB 25 CONN., T6 |
| | DC INPUT | 4D | RED twist pair | POW 12VDC | GYRO FUSE BOX (RED POW), FB2 |

| | DC GND | SE AF | BLK | DC GND/REF | GYRO FUSE BOX BLK via Thru-Hu F-E |
|---|---|---|---|---|---|
| **GYRO, FREE** | S3 | 1 | RED | SIG S3 | SYNCHRO P1:1 T5 |
| db 25 conn | AC CONN/REF S2 | 2 | ORG/GRN | GND/REF S2 | SYNCHRO P1:1 T3 |
| | | 3 | WHT | AC CONN | P.S. T2B, SYNCHRO P1:1 T2 |
| | AC POW | 4 | RED | POW 115 VAC | P.S. T1 |
| | no conn | 5 | | | |
| | AC POW | 6 | BLK | POW 26 VAC | P.S. T3C, SYNCHRO P1:1 T1 |
| | | 7 | WHT | AC CONN | JUMPED TO T3 |
| | UNCAGE INDICATE | 8 | GRN | TTL LO TRUE | PIA-3A BRKOUT T23 |
| | | 9 | WHT/RED | DIG GND | PIA-3A BRKOUT T3 |
| | | 10 | WHT | | JUMPED TO T9 |
| | UNCAGE (HOT) | 11 | WHT | POW | UNCAGE RELAY via ANAL BRD P9 T2 |
| | CAGE (HOT) | 12 | BLK | POW | CAGE RELAY via ANAL BRD P9 T3 |
| | no conn | 13 | | | |
| | POW FOR (UN)CAGE | 14 | RED | POW 24 VDC | SERVO AMP FUSE BLOCK, 5 AMP, FB3 |
| | CAGE INDICATE | 15 | WHT | TTL LO TRUE | PIA-3A BRKOUT T26 |
| | | 16 | WHT | | JUMPED TO T14 |
| | no conn | 17 | | | |
| | S1 | 18 | GRN | SIG S1 | SYNCHRO P1:1 T4 |
| | no conn | 19 | | | |
| **GYRO, FREE, SYNCHRO** | OUTPUT | RIBBON | GRY | DIG/ANAL | HED 34 CONN TO MFI-1 SL 12 |
| RESOLVER BOARD | OUTPUT SEE SCHEM. AND/OR T.C. | | | | |
| NOTE-takes power from | P1:1/J 1:1 | 1 | BLK | IP REF HI | |
| computer, not gyro | | 2 | WHT | IP REF LO | |
| | | 3 | ORG/GRN | S2 | |
| | | 4 | GRN | S1 | |
| | | 5 | RED | S3 | |
| **THRUHULL #2, RS232** | | WHT | GRN | RIBBON | DS9 MFI-1 SL12 T1 |
| TELE CABLE COLORS | | GRN | ORG | RIBBON | DS9 MFI-1 SL12 T3 |
| | | BLK | BRN | RIBBON | DS9 MFI-1 SL12 T5 |
| | | YEL | GRN | RIBBON | DOS MFI-1 SL T1 |
| | | RED | ORG | RIBBON | DOS MFI-1 SL T3 |
| | | BLU | BRN | RIBBON | DOS MFI-1 SL T5 |
| **THRUHULL #1, RS232** | | WHT | GRN | RIBBON | |
| FORWARD | | GRN | ORG | RIBBON | |
| CS TBD USES | | BLK | BRN | RIBBON | |
| | | YEL | GRN | RIBBON | |
| | | RED | ORG | RIBBON | |
| | | BLU | BRN | RIBBON | |
| **TRITEK PROFILER SONAR** | DATA OUT | A | RED | RS 232 | FLYING CONN |
| FLYING CONN + | DATA IN | B | GRN | RS 232 | " |
| 10 PIN BULKN COLORS | DC POW | C | WHT | + 24 VDC | " |
| | GND/REF | D | BLK | GND/REF | " |
| | ANALOG OUT | E | ORG | ANALOG DC | " |
| | HOUSING EARTH | NO CONN | | | |

| TRITEX SCANNER SONAR | DATA OUT | A | RED/BLK | RS 232 | FLYING CONN |
|---|---|---|---|---|---|
| FLYING CONN + | DATA IN | B | GRN/BLK | RS 232 | " |
| 10 PIN BULKH COLORS | DC POW | C | WHT/BLK | + 24 VDC | " |
| | GND/REF | D | BLU | GND/REF | " |
| | ANALOG OUT | E | ORG/BLK | ANALOG DC | " |
| | HOUSING EARTH | NO CONN | | | |

| FLYING OUTBOARD CONN. | DATA OUT | A | RED/4 | RS 232 OUT | PIN 4, WHT INBOARD WIRE |
|---|---|---|---|---|---|
| TRITECH PROFILER | DATA IN | B | GRN/3 | RS 232 IN | PIN 3, GRN INB |
| | DC POW | C | WHT/1 | +24 VDC | PIN 1, WHT INB |
| | GND/REF | D | BLK/2 | GND/REF | PIN 2, BLK & GRY INB |
| | ANALOG OUT | E | ORG/5 | ANALOG DC | NO CONN |

| FLYING OUTBOARD CONN. | DATA OUT | A | RED/BLK/8 | RS 232 OUT | PIN 8, RED INBOARD WIRE |
|---|---|---|---|---|---|
| TRITECH SCANNER | DATA IN | B | GRN/BLK/9 | RS 232 IN | PIN 9, BLK INB |
| | DC POW | C | WHT/BLK/7 | +24 VDC | PIN 7, WHT INB |
| | GND/REF | D | BLU/6 | GND/REF | PIN 6, BLK & GREY INB |
| | ANALOG OUT | E | ORG/BLK/10 | ANALOG DC | NO CONN |

| FORWARD 10 PIN THRU-HULL | DC POW | 1/C | WHT | +24 VDC | ANALOG P.S. T P9-1 |
|---|---|---|---|---|---|
| INBOARD CONN. | POW GND | 2/D | BLK | GND/REF | -24 VDC GND BUSS |
| (TRITECH SONARS) | | 2/D | GRY | GND/REF | SIO-1B CARD, PIN 13, PROF PORT |
| | DATA IN | 3/B | GRN | RS 232 | SIO-1B CARD, PIN 3, PROF PORT |
| | DATA OUT | 4/A | WHT | RS 232 | SIO-1B CARD, PIN 5, PROF PORT |
| | ANALOG SIG | 5/E | NO CONN | | |
| | POW GND | 6/D | BLK | GND/REF | COMMONED TO PIN 2 |
| | | 6/D | GRY | GND/REF | SIO-1B, PIN 13, SCAN PORT |
| | DC POW | 7/C | WHT | + 24 VDC | COMMONED TO PIN 1 |
| | DATA OUT | 8/A | RED | RS 232 | SIO-1B CARD, PIN 5, SCAN PORT |
| | DATA IN | 9/B | BLK | RS 232 | SIO-1B CARD, PIN 3, SCAN PORT |
| | ANALOG SIG | 10/E | NO CONN | | |

| FORWARD 4 PIN THRU-HULL | | | | | |
|---|---|---|---|---|---|
| OUTBRD via FLYING CONN | | 1 (C) | WHT | SIG + | TURBO PROBE PULSE + (RED) |
| (A,B,C,D) | | 2 (B) | BLK | GND/REF | DATASONICS SONAR REF (BLK) |
| | | 3 (D) | GRN | GND/REF | TURBO PROBE REF (BLK) |
| | | 4 (A) | RED | SIG + | DATASONIC SONAR SIG + (RED) |

| FORWARD 4 PIN THRU-HULL | | | | | |
|---|---|---|---|---|---|
| INBOARD | | 1 (C) | WHT | SIG + | T PROBE CIRCUIT BOARD T5 |
| | | 2 (B) | BLK | GND/REF | DATASONICS CIRCUIT BOARD INPUT T1 |
| | | 3 (D) | GRN | GND/REF | T PROBE CIRCUIT BOARD T6 |
| | | 4 (A) | RED | SIG + | DATASONICS CIRCUIT BOARD INPUT T4 |

| DATASONICS SONAR TRANSD. | SIG+ | A | RED | SIG + | TO 4-PIN BULKHEAD CONN |
|---|---|---|---|---|---|
| (FLYING CONN) | SIG REF | B | BLK | SIG REF | TO 4-PIN BULKHEAD CONN |

| DATASONICS SONAR BOARD | INPUT CONN. | 4 | RED | SIG + | SONAR SIG, via FWARD BULH CONN P4 |
|---|---|---|---|---|---|
| | INPUT CONN. | 1 | BLK | SIG REF | SONAR SIG, via FWARD BULH CONN P2 |
| THERMISTER | THERM INPUT | | RED | | THERMISTER |
| | THERM INPUT | | GRN | | THERMISTER |
| | 12 PIN | 1 | BLU/BLK | NO CONN | EXT. KEY INPUT |

| | | | | |
|---|---|---|---|---|
| 2 | BLK | POW GND | ANALOG P.S. GND | |
| 3 | RED/WHT | POW 15 VDC | ANALOG P.S. +15 VDC SUPPLY | |
| 4 | BLK | ANAL GND | JUMPED TO T2 | |
| 5 | BLK/WHT-RED | NO CONN | ERROR SIG | |
| 6 | NO CONN | | | |
| 7 | NO CONN | | | |
| 8 | NO CONN | | | |
| 9 | NO CONN | | | |
| 10 | NO CONN | | | |
| 11 | WHT/BLK-RED | SIG + | ICU-2A BRKOUT T13 | |
| 12 | NO CONN | | | |

**DEPTH CELL BOARD**
**DEPTH CELL TRANSD**

| TURBO PROBE BOARD | | 1 | no conn | | |
|---|---|---|---|---|---|
| | POW | 2 | WHT | POW 24 VDC | FUSE BLK 1 (MASTER RELAY) |
| | GND/REF | 3 | BLK | GND/REF | GND REF BUSS |
| | SIG OUT | 4 | WHT | PULSE SIG | TIN BRKOUT T4 |
| | SIG IN | 5 | WHT | SIG + INP | PROBE via 4 PIN THR-H T1 + RED (C) |
| | SIG REF | 6 | GRN | SIG INP REF | PROBE via 4 PIN THR-H T3 + BLK (D) |

| TURBO PROBE TRANSD | SIG + | WHT IN AUV | RED (C) | + SIG | TURBO P CARD via FLY CONN + 4 PIN |
|---|---|---|---|---|---|
| | SIG REF | GRN IN AUV | BLK (D) | SIG REF | TURBO P CARD via FLY CONN + 4 PIN |

**GPS RECEIVER**
**GPS DIFF. RECEIVER**
**GPS ANTENNA**

| TIN-1A slot 7 | 10 | gate 1 | 6 | YELL | RPM SIG | PT SCREW RPM T3 |
|---|---|---|---|---|---|---|
| 610 MEX (A9,B,3) | 8 | gate 2 | 3 | ORG | RPM SIG | STBD SCREW RPM T3 |
| INCL. BRKOUT | 6 | gate 3 | 4 | WHT | RPM SIG | TURBO PROBE T4 |
| (INPUT) | 4 | gate 4 | 1 | | | |
| | 3 | gate 5 | 2 | | | |
| | 19 | GND | 23 | GRY | GND | FIN SERVO BOARD, GND |
| | 20 | GND | 24 | GRY | GND | FIN SERVO BOARD, GND |
| | 1,2 | +15 VDC | | RED-ORG | POW | TERM 0 SL 5 BRKOUT |

| TIN-1A slot 8 | 10 | gate 1 | 9 | GRN/BLK | RPM sig | F.V. THR RPM T3 |
|---|---|---|---|---|---|---|
| 620 MEX (A9,B,4) | 8 | gate 2 | 10 | VIOL | RPM sig | F.H. THR RPM T3 |
| INCL. BRKOUT | 6 | gate 3 | 7 | BLU/WHT | RPM sig | A.V. THR RPM T3 |
| (INPUT) | 4 | gate 4 | 8 | WHT/BLK | RPM sig | A.H. THR RPM T3 |
| | 3 | gate 5 | 5 | | | |
| | 19 | GND | 23 | GRY | GND | FIN SERVO BOARD, GND |
| | 20 | GND | 24 | GRY | GND | FIN SERVO BOARD, GND |
| | 1,2 | +15 VDC | | RED-ORG | POW | TERM 0 SL 5 BRKOUT |

```
TIN-1A  SLOT 9          7   out 1    11           VIOL      CNTRL     FWD TOP FIN, T 1
  640 HEX (A9,8,5)      5   out 2    12           YEL       CNTRL     FWD BOT FIN, T 1
  INCL. BRKOUT          9   out 3    14           ORG       CNTRL     FWD STBD FIN, T 1
  (OUTPUT)              11  out 4    13           RED       CNTRL     FWD PORT FIN, T 1
  5 VDC INJECTION                    17,18,19,20  WHT       5 VDC     FIN SERVO INJECTION BOARD
                        13  out 5    16
                        17  SNC1     15
                        19  GND      23           GRY       GND       FIN SERVO BOARD, GND
                        20  GND      24           GRY       GND       FIN SERVO BOARD, GND
                        1,2 +12 VDC               RED-ORG   POW       TERM 0 SL 5 BRKOUT


TIN-1A  SLOT 10         7 . out 1    17           WHT       CNTRL     Aft. FIN, Top
  600 HEX (A9,8,6)      5   out 2    18           BRN       CNTRL     Aft. FIN, Bottom
  INCL. BRKOUT          9   out 3    20           GRN       CNTRL     Aft.Fin, STBD
  (OUTPUT)             11   out 4    19           ORG       CNTRL     Aft.Fin, Port
  5 VDC INJECTION                    17,18,19,20  WHT       5 VDC     FIN SERVO INJECTION BOARD
                       13   out 5    22
                       15   Fout     21
                       19   GND      23                     GND/REF   INTERN GND + FIN SERVO BOARD GND
                       20   GND      24                     GND/REF   INTERN GND + FIN SERVO BOARD GND
                                     25           GRY       GND/REF   JUMPED TO T23
                                     26           GRY       GND/REF   JUMPED TO T24
                       1,2 +12VDC                 RED-ORG   POW       TERM 0 SL 5 BRKOUT


DAC-28 SLOT 11          1            27           GREY      GND/REF   PORT S SERV T5
  40 HEX (A5)           2            30           RED       Ch.1      PORT S SERV T4
  INCL BRKOUT           3            29           GREY      GND/REF   STBD S SERV T5
  ANALOG SIG. OUT       4            32           ORG       Ch.2      STBD S SERV T4
                        5            31           GREY      GND/REF   F V TH SERV T5
                        6            34           BLUE      CH...     F V TH SERV T4
                        7            33           GREY      GND/REF   F H TH SERV T5
                        8            36           BLK       Ch.4      F H TH SERV T4
                        9            35           GREY      GND/REF   A V TH SERV T5
                        10           38           YEL       CH.4      A V TH SERV T4
                        11           37           GREY      GND/REF   A H TH SERV T5
                        12           40           WHT       Ch.6      A H TH SERV T4
                        13           39                     GND/REF
                        14           42                     Ch.7
                        15           41                     GND/REF
                        16           44                     Ch.8
                        17 +15 VDC   43                     +15 DC PWR   Internal DC-DC Pwr
                        18 +15 VDC   46                     +15 DC PWR     "    "    "
                        19 -15 VDC   45                     -15 DC PWR     "    "    "
                        20 -15 VDC   48                     -15 DC PWR     "    "    "


ADC-2 (ICN-28) SLT 6   CURRENT MON  0            VIOL      ANAL. SIG   PORT SCREW SERVO A T8
  20 HEX (A4)          CURRENT MON   1            BLU       ANAL. SIG   STBD SCREW SERVO A T8
  INCL BRKOUT                        2
  ANALOG INPUTS        CURRENT MON   3            YEL       ANAL. SIG   F V TH SERVO AMP T8
                       CURRENT MON   4            WHT       ANAL. SIG   F H TH SERVO AMP T8
                       CURRENT MON   5            BLU       ANAL. SIG   A V TH SERVO AMP T8
                       CURRENT MON   6            ORG       ANAL. SIG   A V TH SERVO AMP T8
  DEPTH SIGNAL         DEPTH         7            YEL       ANAL. SIG   DEPTH CELL CARD T10
```

| | | | | | |
|---|---|---|---|---|---|
| RATE GYRO | PITCH RATE | 8 | BRN-BLU | ANAL. SIG | Ptch Rate Gyro, PIN D |
| RATE GYRO | ROLL RATE | 9 | BLK-BLU | ANAL. SIG | Roll Rate Gyro, PIN D |
| RATE GYRO | YAW RATE | 10 | WHT-BLU | ANAL. SIG | Yaw Rate Gyro, PIN D |
| VERTICAL GYRO | PITCH ANGLE | 11 | BRN | ANAL. SIG | Ptch Ang. Gyro, PIN F |
| VERTICAL GYRO | ROLL ANGLE | 12 | VIOL | ANAL. SIG | Roll Ang. Gyro, PIN K |
| SONAR | DATASONICS | 13 | WHT/BLK/RED | ANAL. SIG | DATAS SONAR CARD, T11 |
| | TRIT PROF? | 14 | | | |
| | TRIT SCANNER? | 15 | | | |
| GND, JUMPED | ANAL/DIG | P2 | GREY | GND/REF | AN/DIG GND ANAL P.S. |

| | | | | | |
|---|---|---|---|---|---|
| ADC-1 (ICU-2A), SL 5 | +15 VDC SUPPLY | 0 | RED/WHT | ANAL DIAGN | + 15V TERM ANAL. P.S. |
| 10 HEX, ANALOG P.S. | | 0 | RED/ORG | POW +15VDC | TIM CARDS PIN 1,2 (4) |
| INCL. BRKOUT | -15 VDC SUPPLY | 1 | RED/BLK | ANAL DIAGN | - 15V TERM ANAL P.S. |
| DIAGNOSTICS | +5 VDC SUPPLY | 2 | RED | ANAL DIAGN | + 5V TERM ANAL P.S. |
| | +10 VDC SUPPLY | 3 | ORG/RED | ANAL DIAGN | + 10V TERM ANAL P.S. |
| | -10VDC SUPPLY | 4 | ORG/BLK | ANAL DIAGN | - 10V TERM ANAL P.S. |
| | | 5 | | | |
| | | 6 | | | |
| | | 7 | | | |
| | | 8 | | | |
| | | 9 | | | |
| | | 10 | | | |
| | | P2 | GREY | GND/REF | AN/DIG GND ANAL P.S. |

| | | | | | | |
|---|---|---|---|---|---|---|
| PIA-3A, 80 HEX, SL 4 | 1 | +12 | not conn | NC | | |
| TTL INPUTS P2 VIA1 | 2 | -12 | not conn | 02 | | |
| INCL. BRKOUT | 3 | +5 | | 01 | WHT | + 5VDC | TO SERVO AMP INVERTOR CHIP |
| | 4 | +5 | | 04 | | | |
| | 5 | GND | | 03 | WHT/RED | DIG GND | FROM FR GYRO PIN 9 |
| | | | | 03 | WHT | DIG GND | TO SERVO AMP INVERTOR CHIP |
| | 6 | GND | | 06 | | | |
| | 7 | CB2 | | 05 | | | |
| | 8 | CA2 | | 08 | | | |
| | 9 | CB1 | | 07 | | | |
| | 10 | CA1 | | 10 | | | |
| | 11 | PB7 | | 09 | | | |
| | 12 | PA7 | | 12 | | | |
| | 13 | PB6 | | 11 | | | |
| | 14 | PA6 | | 14 | | | |
| | 15 | PB5 | | 13 | | | |
| | 16 | PA5 | | 16 | | | |
| | 17 | PB4 | | 15 | | | |
| | 18 | PA4 | | 18 | | | |
| | 19 | PB3 | | 17 | | | |
| | 20 | PA3 | | 20 | | | |
| | 21 | PB2 | | 19 | | | |
| | 22 | PA2 | | 22 | | | |
| | 23 | PB1 | | 21 | | | |
| | 24 | PA1 | | 24 | | | |
| FG UNCAGE INDICATE | 25 | PB0 | | 23 | grn | TTL LO/TRUE | FREE GY DB25, PIN 8 |
| FG CAGE INDICATE | 26 | PA0 | | 26 | wht | TTL LO/TRUE | FREE GR DB25, PIN 15 |

```
PIA-3A con't, slot 4          1   +12    Not conn
TTL OUTPUTS P2 VIA0           2   -12    Not conn
   INCL BRKOUT                3   +5         28
                             4   +5         27
                             5   GND        30
                             6   GND        29
                             7   CB2        32
                             8   CA2l       31
                             9   CB1        34
                            10   CA1        33
                            11   PB7        36
P.S. ON/OFF                 12   PA7 +/- 15V  35      wht       TTL HI/TRU    ANAL P.S. T P2-1
                            13   PB6        38
P.S. ON/OFF                 14   PA6 + 5V   37      wht/brn   TTL HI/TRU    ANAL P.S. T P1-3
                            15   PB5        40
THRUSTER SERVO INHIBIT      16   PA5 A.H.Thr  39    wht-39    TTL INIT HI   INVERTER BOARD T 8
                            17   PB4        42
THRUSTER SERVO INHIBIT      18   PA4 A.V.Thr  41    wht-41    TTL INIT HI   INVERTER BRD T 6
                            19   PB3        44
THRUSTER SERVO INHIBIT      20   PA3 F.H.Thr  43    wht-43    TTL INIT HI   INV BRD T 45
TRITEC SONAR ON/OFF         21   PB2 Tritech  46    green     TTL LO/TRU    ANAL P.S. P10-1
THRUSTER SERVO INHIBIT      22   PA2 F.V.Thr  45    wht-45    TTL INIT HI   INV BRD T 2
FREE GYRO                   23   PB1 Uncage   48    grn/blk   TTL LO/TRU    ANAL P.S. P10-2
SCREW SERVO INHIBIT         24   PA1 Stb Screw  47  wht-47    TTL INIT HI   INV BRD T 17
FREE GYRO                   25   PB0 Cage   50      grn/wht   TTL LO/TRU    ANAL P.S. P10-3
SCREW SERVO INHIBIT         26   PA0 Port screw  49  wht-49   TTL INIT HI   INV BRD T 15


TTL INVERTER FOR
PIA-3A TTL OUTPUTS
TO SERVO AMPS

A.H. THR INHIB            T39      8-12      ORG     TTL LO/TRU    A.H.TH SERVO AMP T-11
A.V. THR INHIB            T41      6-14      GRN     TTL LO/TRU    A.V.TH SERVO AMP T-11
F.H. THR INHIB            T43      4-16      YEL     TTL LO/TRU    F.H.TH SERVO AMP T-11
F.V. THR INHIB            T45      2-18      BRN     TTL LO/TRU    F.V.TH SERVO AMP T-11
STB SCREW INHIB           T47      17-3      VIOL    TTL LO/TRU    STB SCRW SERV AMP T11
PRT SCREW INHIB           T49      15-5      BLUE    TTL LO/TRU    PT SCRW SERVO AMP T11
+5VDC PWR, BRKOUT         T1       1,10,19   WHT     PWR           PIA-3A BRKOUT T1
GND, PIA BRKOUT           T3       20        WHT     DIG GND       PIA-3A BRKOUT T3


        WFI-1 address 700 hex slot (A9,8,7) slot 12
     NO BRKOUT, DIRECT FLAT RIBBON CONN.
  ASSIGN ON 24 PIN CONN. ON WFI-1 BOARD FROM SYNCHRO DEMOD.
     All signals to/from P2 to Syncro to Digital Board from D6
     P2   Function  Signal      P2   Function  Signal
     1    +12                   2    -12
     3    +5                    4    +5
     5    GND                   6    GND
     7    CB2                   8    CA2
     9    CB1                   10   CA1
     11   PB7    Not Inhibit    12   PA7    Bit 7
     13   PB6    Busy           14   PA6    Bit 6
     15   PB5    Bit 13         16   PA5    Bit 5
     17   PB4    Bit 12         18   PA4    Bit 4
     19   PB3    Bit 11         20   PA3    Bit 3
     21   PB2    Bit 10         22   PA2    Bit 2
     23   PB1    Bit 9          24   PA1    Bit 1
     25   PB0    Bit 8          26   PA0    Bit 0
     27   No connection         28   No connection
     29   Timer Out0    NC      30   Timer Gate0   NC
```

| | | | | | |
|---|---|---|---|---|---|
| 26 | : | Out1 | NC | 32 | : Gate1 NC |
| 30 | : | Out2 | NC | 34 | : Gate2 NC |

| | | | | | |
|---|---|---|---|---|---|
| MFI-1 con't, slot 12 | GND | PIN 1 | RIB-GRN | GND | THRU-HULL #2, WHT |
| CTR 10 pin conn. | NC | PIN 2 | | | |
| DB9 RS232 conn. | TXD | PIN 3 | RIB-ORG | CONN | THRU-HULL #2, GRN |
| NO BRKOUT, DIRECT CONN | NC | PIN 4 | | | |
| | RXD | PIN 5 | RIB-BRN | CONN | THRU-HULL #2, BLK |
| | DTR | PIN 6 | | | |
| | RTS | PIN 7 | | | |
| | DCD | PIN 8 | | | |
| | CTS | PIN 9 | | | |
| | NC | PIN 10 | | | |

| | | | | | |
|---|---|---|---|---|---|
| SESSIO-19 BOARD | DATA IN | PIN 3 | RIBBON, ORG | RS 232 | 10 PIN FWARD THRU-HULL CONN, PIN 3 |
| RS232, TRITECH PROFILER | DATA OUT | PIN 5 | RIB, GRN | RS 232 | 10 PIN FWARD THRU-HULL CONN, PIN 4 |
| | GND/REF | PIN 13 | RIB, ORG | RS 232 | 10 PIN FWARD THRU-HULL CONN, PIN 2 |
| RS 232, TRITECH SCANNER | DATA IN | PIN 3 | RIB, ORG | RS 232 | 10 PIN FWARD THRU-HULL CONN, PIN 9 |
| | DATA OUT | PIN 5 | RIB, GRN | RS 232 | 10 PIN FWARD THRU-HULL CONN, PIN 8 |
| | GND/REF | PIN 13 | RIB, ORG | RS 232 | 10 PIN FWARD THRU-HULL CONN, PIN 6 |

# APPENDIX C   CENTER OF GRAVITY CALCULATION

The calculation of the center of gravity for the AUV is provided on the following page.

For each item shown, the location of its individual center of gravity, relative to the X and Y datum, is listed, along with its weight and first moments in the X and Y directions. The location of the center of gravity is shown at the bottom of the page.

# BUOYANCY TEST 02/04/94

| ITEM | Xin | Yin | Wt(lb) | Mx | My |
|---|---|---|---|---|---|
| FWD VERT THRUSTER ASSY | 14.0 | 10.0 | 5.0 | 70.0 | 50.0 |
| FWD HORIZ. THRUSTER ASSY | 6.3 | 7.0 | 5.5 | 34.4 | 38.5 |
| AFT VERT. THRUSTER ASSY | 49.0 | 8.5 | 5.0 | 245.0 | 42.5 |
| AFT HORIZ THRUSTER ASSY | 56.0 | 6.5 | 5.5 | 308.0 | 35.8 |
| MASTER RELAY | 10.0 | 11.0 | 0.5 | 5.0 | 5.5 |
| BATT. COMPUTER, ANALOG, 2 FWD | 20.5 | 8.0 | 54.0 | 1107.0 | 432.0 |
| BATT. MOTORS, SONAR, 2 AFT | 41.8 | 7.6 | 54.0 | 2254.5 | 410.4 |
| BILGE PLATES, 2 FWD | 9.5 | 8.0 | 3.2 | 30.4 | 25.6 |
| BILGE PLATES, 2 MID | 31.3 | 7.8 | 4.0 | 123.4 | 30.8 |
| BILGE PLATES, 2 AFT | 50.0 | 7.6 | 2.5 | 125.0 | 19.0 |
| HULL 8 SERVOS, MPROP, 4 PLATES | 33.3 | 7.9 | 150.6 | 5007.4 | 1189.7 |
| NOSE, EMPTY LESS 1LB BUOY. | -7.5 | 8.0 | 1.3 | -9.8 | 10.4 |
| FINS, 8, META CENTER AT CG | 31.3 | 7.8 | 5.1 | 159.4 | 39.8 |
| THRUSTER P.S., 4 Midship | 31.3 | 8.0 | 6.4 | 200.0 | 51.2 |
| MAIN PROP P.S., 2 fwd | 14.5 | 8.0 | 3.2 | 46.4 | 25.6 |
| COMPUTER/ANALOG P.S. (2) | 21.0 | 8.0 | 4.2 | 88.2 | 33.6 |
| VERT. GYRO w/BRACKET | 14.0 | 13.0 | 2.0 | 28.0 | 26.0 |
| RATE GYRO(s) | 13.0 | 3.0 | 3.9 | 50.7 | 11.7 |
| FREE GYRO + MOUNT | 49.0 | 2.3 | 3.3 | 159.3 | 7.5 |
| INVERTER FOR F. GYRO | 47.5 | 12.8 | 1.4 | 66.5 | 17.9 |
| NUT PLATE | 33.0 | 7.8 | 4.5 | 148.5 | 35.1 |
| OS 9 CAGE (right) | 31.3 | 5.0 | 4.2 | 129.7 | 20.8 |
| OS 9 CARDS (0.45lb x) 12 | 31.3 | 5.0 | 5.4 | 168.8 | 27.0 |
| 486 CAGE (left) -lead | 31.3 | 10.0 | 3.6 | 114.1 | 36.5 |
| 486 CARDS (0.45lb x) 3 -lead | 31.3 | 10.0 | 1.4 | 42.2 | 13.5 |
| RIBBON CABLE INTERFACE (4) | 41.0 | 7.8 | 1.5 | 61.5 | 11.7 |
| TURBO-PROBE INCL. MOUNT | -2.0 | 4.0 | 3.4 | -6.8 | 13.6 |
| WIRING, MISC. | 31.3 | 7.8 | 3.0 | 93.8 | 23.4 |
| DIFF. GPS REC.+ANT. (0.9LBS) | | | 0.0 | 0.0 | 0.0 |
| GPS RECEIVER | | | | 0.0 | 0.0 |
| GPS ANTENNA + MOUNT | 10.5 | 4.5 | 1.0 | 10.5 | 4.5 |
| TOPSIDE THRU-HULLS | 14.0 | 8.0 | 3.0 | 42.0 | 24.0 |
| T725 SCANNING SONAR | -8.0 | 10.0 | 2.6 | -20.8 | 26.0 |
| T1000 PROFILING SONAR | -5.0 | 10.0 | 2.6 | -13.0 | 26.0 |
| TRITECH SONAR MOUNT, WIRES | -7.0 | 10.0 | 3.0 | -21.0 | 30.0 |
| DATASONICS SONAR + MOUNT, WIRE | -4.0 | 6.0 | 2.4 | -9.6 | 14.4 |
| BUOYANCY, SONARS | -6.0 | 9.5 | -2.0 | 12.0 | -19.0 |
| BUOYANCY, SUPP'S, T PROBE | -4.0 | 8.0 | -0.6 | 2.4 | -4.8 |
| | | | | | |
| TRIM LEAD by F.GYRO INV. | 51.0 | 12.8 | 4.5 | 229.5 | 57.6 |
| TRIM LEAD, aft | 63.0 | 8.3 | 5.9 | 371.7 | 49.0 |
| TRIM LEAD, aft of computers | 38.0 | 7.8 | 8.9 | 338.2 | 69.4 |
| TRIM LEAD | 51.0 | 4.0 | 5.0 | 255.0 | 20.0 |
| TRIM LEAD, fwd of computers | 24.5 | 6.5 | 4.4 | 107.8 | 28.6 |
| TRIM LEAD, tweak | 38.0 | 8.3 | 0.3 | 13.3 | 2.9 |

| | | lbs-TOT | | | |
|---|---|---|---|---|---|
| TOTALS | | | 388.5 | 12155.2 | 3010.7 |

| | | | | | |
|---|---|---|---|---|---|
| C.G., X,Y INCHES FROM DATUM | | | | 31.29 | 7.75 |
| EST. RESERVE BUOYANCY (FRESH) - LBS. | | | 0.5 | | |

NOTE: X DATUM IS FORWARD OUTER HULL EDGE, POSITIVE AFT
      Y DATUM IS INNER STBD HULL SIDE, POSITIVE TO PORT
      DRY C.G.(in)  X,Y  31.25, 7.75

# APPENDIX D    CENTER OF BUOYANCY CALCULATION

The calculation of the center of buoyancy for the AUV is provided on the following page.

For each item shown, the location of its individual center of gravity, relative to the X, Y and Z datum, is listed, along with its weight and first moment in the Z direction. The location of the center of buoyancy is shown at the bottom of the page.

| ITEM | Xin | Yin | Zin | Wt(lb) | Mz |
|------|-----|-----|-----|--------|-----|
| FWD VERT THRUSTER ASSY | 14.0 | 10.0 | 4.8 | 5.0 | 23.8 |
| FWD HORIZ. THRUSTER ASSY | 6.3 | 7.0 | 4.8 | 5.5 | 26.1 |
| AFT VERT. THRUSTER ASSY | 48.0 | 8.5 | 4.8 | 5.0 | 23.8 |
| AFT HORIZ THRUSTER ASSY | 56.0 | 6.5 | 4.8 | 5.5 | 26.1 |
| MASTER RELAY | 10.0 | 11.0 | 1.0 | 0.5 | 0.5 |
| NUT PLATE | 33.0 | 7.8 | 9.5 | 4.5 | 42.8 |
| DIFF GPS REC.+ ANT | | | | | 0.0 |
| GPS RECEIVER | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| GPS ANTENNA, MOUNT, WIRING | 10.5 | 4.5 | 13.0 | 1.0 | 13.0 |
| BATT. COMPUTER, ANALOG, 2 FWD | 20.5 | 8.0 | 3.5 | 54.0 | 189.0 |
| BATT. MOTORS, SONAR, 2 AFT | 41.8 | 7.6 | 3.5 | 54.0 | 189.0 |
| BILGE PLATES, 2 FWD | 9.5 | 8.0 | 0.4 | 3.2 | 1.3 |
| BILGE PLATES, 2 MID | 31.3 | 7.8 | 0.4 | 4.0 | 1.6 |
| BILGE PLATES, 2 AFT | 50.0 | 7.6 | 0.4 | 2.5 | 1.0 |
| HULL 8 SERVOS, MPROP, 4 PLATES | 33.3 | 7.9 | 4.8 | 150.6 | 715.4 |
| NOSE, EMPTY, less 1 lb. buoy | -7.5 | 8.0 | 4.8 | 1.3 | 6.2 |
| FINS, 8, META CENTER AT CG | 31.3 | 7.8 | 4.8 | 5.1 | 24.2 |
| THRUSTER P.S., 4 midship | 31.3 | 8.0 | 4.5 | 6.4 | 28.8 |
| MAIN PROP P.S., 2 fwd | 14.5 | 8.0 | 4.5 | 3.2 | 14.4 |
| COMPUTER/ANALOG P.S. (2) | 21.0 | 8.0 | 8.0 | 4.2 | 33.6 |
| VERT. GYRO w/BRACKET | 14.0 | 13.0 | 3.0 | 2.0 | 6.0 |
| RATE GYRO(s) | 13.0 | 3.0 | 2.5 | 3.9 | 9.8 |
| FREE GYRO + MOUNT | 49.0 | 2.3 | 4.0 | 3.3 | 13.0 |
| INVERTER FOR D.G. | 47.5 | 12.8 | 3.0 | 1.4 | 4.2 |
| TOPSIDE THRU-HULLS | 14.0 | 8.0 | 10.0 | 3.0 | 30.0 |
| OS 9 CAGE (right) | 31.3 | 5.0 | 5.5 | 4.2 | 22.8 |
| OS 9 CARDS (0.4 lb x) 12 | 31.3 | 5.0 | 5.5 | 5.4 | 29.7 |
| 486 CAGE (left) | 31.3 | 10.0 | 5.5 | 3.6 | 20.1 |
| 486 CARDS (0.4 lb x) 3 | 31.3 | 10.0 | 5.5 | 1.4 | 7.4 |
| RIBBON CABLE INTERFACE (4) | 41.0 | 7.8 | 7.0 | 1.5 | 10.5 |
| WIRING, MISC. | 31.3 | 7.8 | 8.0 | 3.0 | 24.0 |
| TURBO-PROBE INCL. MOUNT | -2.0 | 4.0 | 4.0 | 3.4 | 13.6 |
| DATASONICS SONAR, MOUNT, WIRES | -4.0 | 6.0 | 2.5 | 2.4 | 6.0 |
| T725 SCANNING SONAR | -8.0 | 10.0 | 5.5 | 2.6 | 14.3 |
| T1000 PROFILING SONAR | -5.0 | 10.0 | 5.5 | 2.6 | 14.3 |
| TRITECH SONAR MOUNT, WIRES | -7.0 | 10.0 | 5.5 | 3.0 | 16.5 |
| BUOYANCY, SONARS | -6.0 | 9.5 | 5.5 | -2.0 | -11.0 |
| BUOYANCY, SUPP'S, T-PROBE | -4.0 | 8.0 | 5.0 | -0.6 | -3.0 |
| | | | | | 0.0 |
| TRIM LEAD, by fr gyro inv | 51.0 | 12.8 | 1.0 | 4.5 | 4.5 |
| TRIM LEAD, AFT | 63.0 | 8.3 | 3.0 | 5.9 | 17.7 |
| TRIM LEAD, aft of computer | 38.0 | 7.8 | 2.5 | 7.2 | 18.0 |
| TRIM LEAD, by fr gyro | 51.0 | 4.0 | 1.0 | 5.0 | 5.0 |
| TRIM LEAD, forw of computer | 24.5 | 6.5 | 2.5 | 6.1 | 15.3 |
| TRIM LEAD, tweak | 38.0 | 8.3 | 8.0 | 0.3 | 2.8 |

| TOTALS | | | | lbs-TOT | 388.5 | 1651.8 |
|--------|--|--|--|---------|-------|--------|

BG=CTR-BUOYz - CGz, INCHES                                      0.50
RESERVE BUOYANCY (FRESH) LBS.-est.                       0.5

NOTE: X DATUM IS FORWARD OUTER HULL EDGE, POSITIVE AFT
      Y DATUM IS INNER STBD HULL SIDE, POSITIVE TO PORT
      Z DATUM IS INNER HULL BOTTOM, POSITIVE UP
      CTR-BUOY(in)  X,Y,Z  31.25, 7.75, 4.75

# APPENDIX E    FREE GYRO/SYNCHRO BOARD WIRING DIAGRAM

The wiring diagram for the free directional gyro and the synchro to digital converter is provided on the following page.

SDC1740

SSR

CR2

non-invert
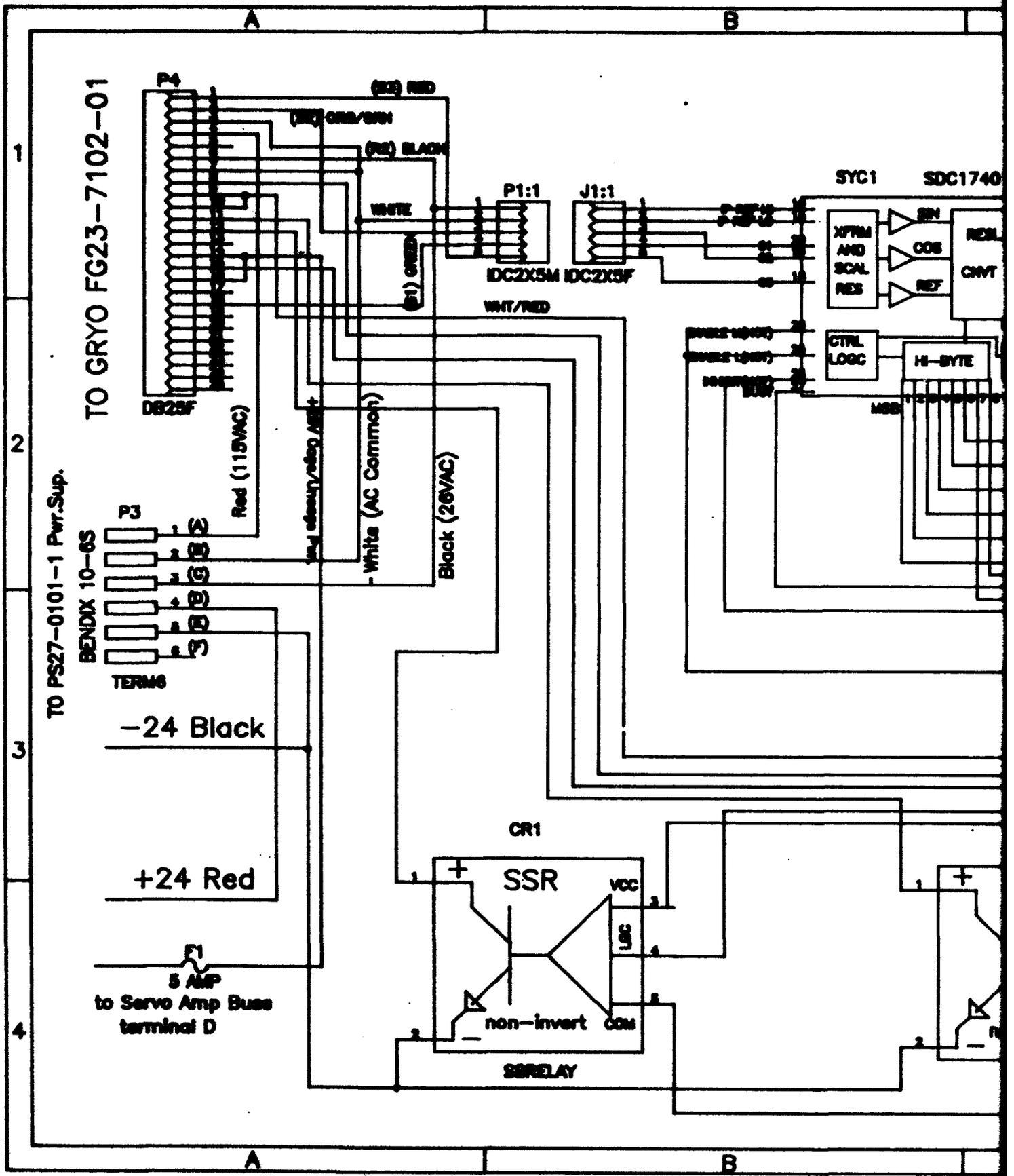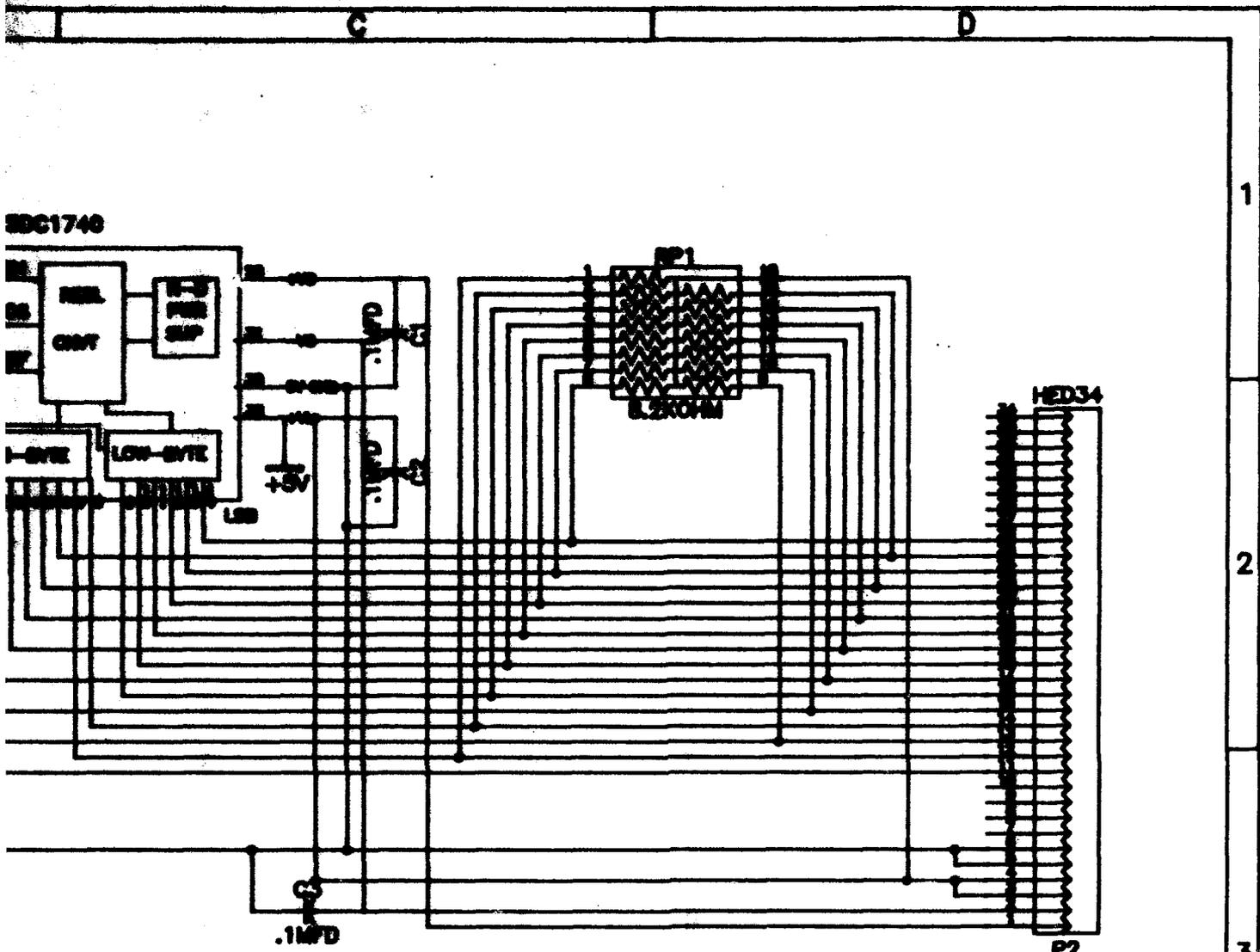
Digital Ground PIA Terminal 3

Uncage indicate Lo True PIA Terminal 23

Cage indicate Lo True PIA Terminal 26

Cage Control Lo True PIA Terminal 50

VCC +5V

Uncage Control Lo True PIA Terminal 48

COMMON (Digital Ground)

HED34

P2

+5V

.1MFD
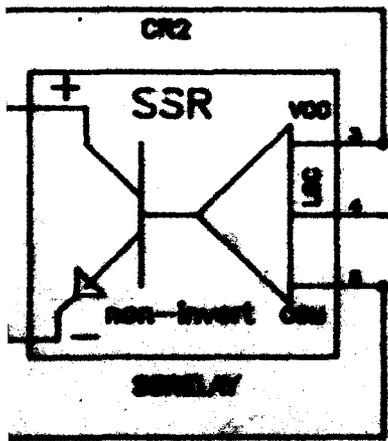
| Title | SYNCRO BOARD/DG SYSTEM | | |
|---|---|---|---|
| Size B | Number Design:T.Christian | | Rev 2.0 |

# APPENDIX F   KALMAN FILTER SUBPROGRAM

The subprogram for the Kalman filter, in C source code, is provided on the following pages.  Velocity and acceleration data is obtained by extracting an estimate of the derivative, and second derivative, of sonar range data using the subprogram.   The filter also provides a smooth position estimate.

```
/* KALMAN FILTER FOR SONAR RANGE*/
kalman(yk,xk_0,xk_1,xk_2)

    double yk,*xk_0,*xk_1,*xk_2;
{
    double xk1_0,xk1_1,xk1_2;
    double phiI[3][3],h[3],b[3],lk[3],res,q,rv;

    /* a=[0 1 0;0 0 1;0 0 0]; phii=expm(a*0.1); where dt = 0.1 */
    b[0] = 0.0;
    b[1] = 0.0;
    b[2] = 1.0;

    /* phii = [1.0     0.1      0.005
               0.0     1.0      0.1
               0.0     0.0      1.0] */
    phii[0][0] = 1.0;
    phii[0][1] = 0.1;
    phii[0][2] = 0.005;
    phii[1][0] = 0.0;
    phii[1][1] = 1.0;
    phii[1][2] = 0.1;
    phii[2][0] = 0.0;
    phii[2][1] = 0.0;
    phii[2][2] = 1.0;

    rv = 0.1;
    q  = 0.01;
    /*thres = 2.0; Global Now */

    /* h = [1 0 0]; */
    h[0] = 1.0;
    h[1] = 0.0;
    h[2] = 0.0;

    if(kal_init == 1)
    {
        *xk_0 = yk;
        *xk_1 = 0.0;
        *xk_2 = 0.0;

        /* xk1=xk; */
        xk1_0 = *xk_0;
        xk1_1 = *xk_1;
        xk1_2 = *xk_2;
    }

    /* set lk = const. */
    lk[0] = 0.2544;
    lk[1] = 0.3727;
    lk[2] = 0.2731;
```

```c
/* xk1(:,i)=phii*xk(:,i); */
xk1_0 = phii[0][0]*(*xk_0) + phii[0][1]*(*xk_1) + phii[0][2]*(*xk_2);
xk1_1 = phii[1][0]*(*xk_0) + phii[1][1]*(*xk_1) + phii[1][2]*(*xk_2);
xk1_2 = phii[2][0]*(*xk_0) + phii[2][1]*(*xk_1) + phii[2][2]*(*xk_2);

/* res=(yk(i)-h*xk1(:,i)); */
res = yk - (h[0]*xk1_0 + h[1]*xk1_1 + h[2]*xk1_2);

/*  Set res = 0.0 if larger than threshold */
if(fabs(res) > thres)
{
    res = 0.0;
}

/*xk(:,i+1)=xk1(:,i) + lk*res; */
*xk_0 =  xk1_0 + lk[0]*res;
*xk_1 =  xk1_1 + lk[1]*res;
*xk_2 =  xk1_2 + lk[2]*res;
```

# APPENDIX G AUV SIMULATION MODEL

The program, in MATLAB source code, which simulates the AUV maneuvering in a horizontal plane is provided on the following pages.

112

```
AUV SIMULATION MODEL: MANEUVERING IN HORIZONTAL PLANE

        clear;

%       LOAD DATA FROM TEST
        load ser1256;
        load   d1256;
        s   = ser1256;
        h   =   d1256;
        NP  =     800;
        dt  =     0.1;
        t   = [0:dt:dt*NP];

%       DERIV OF YAW;
        hd(1) = (h(2,2)-h(1,2))/0.1;
        for I = 2:NP,
            hd(I) = (h(I+1,2)-h(I-1,2))/0.2;
        end;

%       FIND SCALE AND BIAS
        hr          = h(1:NP,3)';
        P           = polyfit(hr,hd,1);


%       INIT CONDS
        Xs(1)       =     0.0;
        Ys(1)       = s(1,3);
        u(1)        =     0.0;
        v(1)        =     0.0;
        r(1)        = h(1,3);
        rdot        =     0.0;
        Ydots(1) =     0.0;
        Xdot(1) =     0.0;
        GF          =      pi;              % for RW, FW, GF = pi;
        PSI(1)    = GF+h(1,2);

%       POSITION ORDERS
        PSIcom    =    GF*180/pi-0.0;    % give PSIcom in degrees
        Xcom      =     0.0;
        Ycom      =     4.0;

%       CONTROL LAW GAINS
        RW        =    -1.0;            % for RW,      RW = -1.0;
        FW        =     1.0;            % for FW,      FW = -1.0;
        Kpsi      =    80.0;
        Tdr       =     1.0;
        Kr        =   Kpsi*Tdr;
        Kx        =     0.0;            % for YAW, LAT test, Kx = 0.0;
        Tdx       =     3.0;
        Ku        =   Kx*Tdx;
        Ky        =    12.0;            % for YAW, LONG test, Ky = 0.0;
        Tdy       =     3.0;
        Kv        =   Ky*Tdy;
```

```
% AUV DIMENSIONS
NMV      =    24.0;
NSP      =     5.0;
TF       =     2.0;
a        =    13.52;
DF       =    23.0/12.0;
Xg       =     0.125/12.0;
xs       =     3.0;
X(1)     =    Xs(1)-xs*cos(PSI(1));
Y(1)     =    Ys(1)-xs*sin(PSI(1));
Ydot(1)  =    Ydots(1)-xs*r(1);

% HYDRODYNAMIC COEFFS;
Xuu      =    -3.0;
Xudot    =    -0.06*377.67;
Yvv      =    -0.5*51.72;
Yrr      =     0.01187*377.67;
Yvdot    =    -0.04*377.67;
Yrdot    =    -0.00178*2756.81;
Nvv      =    -0.00769*377.67;
Nrr      =    -0.04*2756.81;
Nvdot    =    -0.001*2756.81;
IzzNrdot =    45.0-(-0.002*20137.50);

for I = 1:NP,

% CALCULATE VOLTAGES
        VFTH(I) = -(Kpsi*(PSI(I)-PSIcom*pi/180)+Kr*r(I)...
                   +RW*(Ky*(Ys(I)-Ycom)+Kv*Ydot(I)));
            if VFTH(I) > NMV, VFTH(I) = NMV; end;
            if VFTH(I) < -NMV, VFTH(I) = -NMV; end;

        VATH(I) = (Kpsi*(PSI(I)-PSIcom*pi/180)+Kr*r(I)...
                   -RW*(Ky*(Ys(I)-Ycom)+Kv*Ydot(I)));
            if VATH(I) > NMV, VATH(I) = NMV; end;
            if VATH(I) < -NMV, VATH(I) = -NMV; end;

        VLS(I)  = -FW*(Kx*(Xs(I)-Xcom)+Ku*Xdot(I));
            if VLS(I) > NMV, VLS(I) = NMV; end;
            if VLS(I) < -NMV, VLS(I) = -NMV; end;

        VRS(I)  = -FW*(Kx*(Xs(I)-Xcom)+Ku*Xdot(I));
            if VRS(I) > NMV, VRS(I) = NMV; end;
            if VRS(I) < -NMV, VRS(I) = -NMV; end;

% CALCULATE FORCES

        FFTH(I) = TF/(NMV^2)*VFTH(I)*abs(VFTH(I));
        FATH(I) = TF/(NMV^2)*VATH(I)*abs(VATH(I));
        FTTH(I) = FFTH(I)+FATH(I);
        NTH(I)  = (FFTH(I)-FATH(I))*DF;
        FLS(I)  = NSP/(NMV^2)*VLS(I)*abs(VLS(I));
        FRS(I)  = NSP/(NMV^2)*VRS(I)*abs(VRS(I));
```

```
%   EQUATIONS OF MOTION
        udot = (m*v(I)*r(I)+Xuu*u(I)*abs(u(I))...
               +FLS(I)+FRS(I))/(m-Xudot);
        vdot = (Yvv*v(I)*abs(v(I))+Yrr*r(I)*abs(r(I))-m*u(I)*r(I)...
               +Yrdot*rdot+FTTH(I))/(m-Yvdot);
        rdot = (Nvdot*vdot+Nvv*v(I)*abs(v(I))+Nrr*r(I)*abs(r(I))...
               +MTH(I))/(IzzNrdot);
        Xdot(I+1)  = u(I)*cos(PSI(I))-v(I)*sin(PSI(I));
        Ydot(I+1)  = u(I)*sin(PSI(I))+v(I)*cos(PSI(I));
        Ydots(I+1) = Ydot(I+1)+xs*r(I);

%   EULER INTEGRATION
        u(I+1)    = u(I)+udot*dt;
        v(I+1)    = v(I)+vdot*dt;
        r(I+1)    = r(I)+rdot*dt;
        PSI(I+1)  = PSI(I)+r(I)*dt;
        X(I+1)    = X(I)+Xdot(I+1)*dt;
        Y(I+1)    = Y(I)+Ydot(I+1)*dt;
        Xs(I+1)   = X(I+1)+xs*cos(PSI(I+1));
        Ys(I+1)   = Y(I+1)+xs*sin(PSI(I+1));
    end
```

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